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Water Source Partitioning for Shrubland Transpiration in a Mixed Phreatophytic Plant Community

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WATER SOURCE PARTITIONING FOR SHRUBLAND TRANSPIRATION IN A
MIXED PHREATOPHYTIC PLANT COMMUNITY

By

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Bachelor of Science – Biological Sciences
University of Nevada, Las Vegas
2008

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science - Water Resources Management

Water Resources Management Program
College of Sciences
The Graduate College

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ABSTRACT

WATER SOURCE PARTITIONING FOR SHRUBLAND TRANSPIRATION IN A MIXED PHREATOPHYTIC PLANT COMMUNITY

by

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Groundwater in the basins of east central Nevada (Great Basin Desert, NV) has been permitted for export to southern Nevada. These basins are also vulnerable to changes in climate that could lead to declining recharge. Any decline in groundwater levels no matter the driving force could significantly impact phreatophytes (deep rooted shrubs), which utilize water from both the vadose zone and the capillary fringe to meet plant water needs, to support growth, and for overall health. A reduction in groundwater due to these forces could have a significant impact on the decoupling of phreatophytes from what is normally a reliable source of water. Some climate models predict a reduction in annual precipitation over the next 20-30 years throughout much of the western United States (Barnett and Pierce, 2008). Therefore, extensive research is needed to gain a stronger understanding of the coupling of phreatophytes to groundwater prior to pumping and possible climate change. In March 2010, field research was initiated to gain a better understanding of the hydrologic connections between phreatophytes and their environment in Spring Valley, NV. Isotope and soil moisture data collected to 340 cm suggested that the phreatophytic shrub was responding to both groundwater and soil moisture in the vadose zone, with greater reliance on groundwater later in the summer period. Eddy covariance full stand level evapotranspiration (ET_{EC}) estimates were used in conjunction with multiple plant parameters to

assess contributions from groundwater using water balance techniques. Results suggested that the phreatophyte *Sarcobatus vermiculatus* (common name greasewood) was accessing and utilizing groundwater resources while the other three species on site, *Chrysothamnus nauseosus* (rabbitbrush), *Artemisia tridentata* (sagebrush), and *Atriplex confertifolia* (shadscale), appeared to be accessing water only within the upper 100 cm. Data also indicated that rabbitbrush maintained a more favorable water status than other species at this site suggesting rabbitbrush, a non-halophyte, may have been accessing water deeper within the upper 100 cm than other species were not accessing, but was probably not accessing groundwater due to the presence of high levels of soluble salts ($> 50 \text{ dSm}^{-1}$ in soil solution) beyond 100 cm.

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CHAPTER 1 INTRODUCTION

Reductions in annual water recharge in the basins of east central Nevada (Great Basin Desert, NV) associated with climate change could have significant impacts on native plant communities. Groundwater development projects have been proposed to build a pipeline system to convey groundwater from central and eastern Nevada to southern Nevada to meet future water demands (SNWA, 2011; SNWA, 2012). This proposed pipeline system, in conjunction with climate change predictions, may cause additional strain on groundwater resources. Phreatophytes, deep rooted shrubs with the ability to utilize groundwater as a water source, may become more reliant on groundwater sources as the climate changes. A decline in depth to groundwater due to these two impacts could have significant effects on the decoupling of phreatophytes from what is typically a reliable source of water (Harrill and Prudic, 1998). This could further alter the interactions of phreatophytic species with other native vegetation competing for water resources within the vadose zone, the unsaturated zone between the soil surface and groundwater (Busch et al., 1992). This research study provided an overview of the interactions between the known phreatophyte species *Sarcobatus vermiculatus*, a woody halophytic (salt loving) shrub species found throughout the Northwestern United States, with groundwater resources available within Spring Valley. Along with *Sarcobatus vermiculatus* (common name greasewood), this study also investigated water use and evapotranspiration (ET) contribution for *Chrysothamnus nauseosus* (rabbitbrush), *Artemisia tridentata* (sagebrush), and *Atriplex confertifolia* (shadscale).

The goal of this research was to gain a stronger understanding of the water use of mixed shrubland species in the Great Basin prior to groundwater development and possible climate change. The objectives of this research were to utilize field techniques such as eddy covariance, which integrates evapotranspiration from a canopy area, hydrologic balance, isotopic analysis of

soil plant and water samples and physiological parameters to assess the linkage between water use and water source. It was hypothesized that a combination of eddy covariance data, soil moisture, and plant specific measurements could be used to estimate species and community level ET and also the degree of which the species rely on water within the vadose zone versus the groundwater. Furthermore, it was hypothesized that isotopic analyses of stem exudation, soil moisture, and groundwater could be used to assess the dependence for each species on a given water source.

CHAPTER 2 REVIEW OF RELATED LITERATURE

Effects on Water Resources

Barnett and Pierce (2008) provided alarming data stating if conditions in the southwestern United States remain unchanged, live storage in Lake Powell and Lake Mead (Southern Nevada's primary water sources) has a 50 % chance of being completely emptied by 2021. Stream flow reductions of 10-30 % for the Colorado River are not unrealistic given current modeling and statistical calculations. Barnett and Pierce (2008) make the argument that time-dependent water solutions should be created today to avoid conflicts and litigation problems in the future. Climate models predict the western United States will continue on a trend towards a warmer and dryer climate with temperature increases projected at 2 to 4 degrees Celsius (°C) by 2050 with eleven of twelve global models (selected to provide the best simulation of historical runoff for the upper Colorado River Basin) predicting significant drying, with statistical based studies showing the same trend (Barnett and Pierce, 2008; Nash and Gleick, 1991, 1993; McCabe and Wolock, 2007; Christensen et al., 2004). Changes in the Colorado River stream flow resulting from a warmer and dryer climate have driven water managers to seek alternative sources of water for southern Nevada, including the pumping and redistribution of groundwater from northern basins. (SNWA, 2011). In a ruling on March 22, 2012 (Ruling 6164), the Nevada State Engineer issued water rights rulings on the Southern Nevada Water Authority (SNWA) groundwater application for Spring Valley allowing for a total of 61,127 acre-feet per year (afy) of groundwater pumping in Spring Valley alone and a total of 124,988 afy throughout Central Nevada (SNWA, 2012).

Elmore et al. (2006) documented the effects of groundwater pumping on a large natural basin for the purpose of providing water to urban centers in southern California. In Owens Valley, CA,

semiarid plant communities of the Great Basin, similar to those seen in Spring Valley NV, experienced phreatophytic species decoupling from groundwater over the course of thirteen years due to anthropogenic (human induced) groundwater development combined with extended drought that drove groundwater levels below the root zones for the phreatophytic vegetation and led to a shift in ecosystem function from one buffered by drought and stable groundwater levels to a system that was increasingly sensitive to small changes in precipitation (Elmore et al., 2006).

Water Balance and Evapotranspiration

Steinwand et al. (2006) determined that there are varied levels of dependence to groundwater in shrub-dominated communities and that the disappearance of diurnal fluctuations in a phreatophytic vegetation zone could signal a stress-induced plant decoupling from the water table. Field investigations of phreatophyte-induced fluctuations in the water table by Butler et al. (2007) found that variations in water use by phreatophytes were caused by several factors including vegetation size, density, and health and type, specific yield of sediments in the vicinity of the water table, and meteorological drivers of plant water use which included precipitation events and cloud cover. Butler et al. (2007) also suggested that ongoing work should combine methods such as eddy covariance (EC), groundwater oscillations, and isotopic tracers as tools to assist in the differentiation of plant contributions to ET for riparian habitats.

A method for estimating basin level ET of mixed shrub communities in phreatophytic zones within the Great Basin of Nevada was described by Devitt et al. (2010) by determining an empirical relationship between EC data and a vegetation index derived from remotely sensed spectral data provided by LANDSAT. ET rates were highly correlated with plant cover within the phreatophyte area of the basin. Strong diurnal groundwater oscillations late in the growing period signaled a stronger coupling of the greasewood to groundwater (Devitt et al., 2010). ET

totals exceeded precipitation in the study by 55-60 percent, but the study did not attempt to partition out the transpiration from the ET totals (Devitt et al., 2008). The use of a water balance approach [$ET = \text{Precipitation} - \text{Drainage} - \text{Change in Storage}$] was successfully utilized as a means to extract groundwater contribution to ET by subtracting precipitation values from the eddy covariance values for a growing period (Devitt et al., 2008). When drainage is assumed to be zero, the difference between the measured ET value and precipitation can be partitioned to groundwater extraction by phreatophytes when ET exceeds precipitation (Devitt et al., 2008). Devitt and Bird (2015) suggest possible weakness in this approach, but also suggest that in combination with other parameters (e.g., soil moisture, groundwater oscillations, plant specific data) the estimate can be a viable way of determining contribution of groundwater to overall ET values.

Ground Based Normalized Difference Vegetation Index

Vegetation indices based on visible and near infrared reflectance have been successful in estimating ET. A common vegetation index that has been used is the Normalized Difference Vegetation Index (NDVI) which is the normalized ratio of red and near infrared reflectance (NIR) where $NDVI = (NIR - RED)/(NIR + RED)$ (Baghzouz et al., 2010; Seevers and Ottman, 1994; Rouse et al., 1974). A satellite based NDVI remote sensing technique has been widely used for many years to acquire regional and global estimations of surface energy fluxes such as ET, but satellite data lack temporal resolution because satellite overpass data collection only occurs every 11 – 16 days (Allen et al., 2011; Baghzouz et al., 2010; Moran et al., 1989; Nagler et al., 2005).

Baghzouz et al. (2010) utilized ground based NDVI to provide continuous time series analysis of individual shrub species and soil surface characteristics for two different semi-arid

environmental settings located in the Great Basin Desert. Baghzouz (2010) found that ground based NDVI provided temporal information on the phenological cycle of different shrub species that allowed for a clear identification of the length of the active growing season.

Stable Isotopes and Water Source Partitioning

Stable isotopic fractionation, the thermodynamic process of exchanging isotopes between any two molecular phases participating in a reaction (Urey et al., 1951), has been used to determine the plant water source for over 20 years (Chimner and Cooper, 2004; Ehleringer, 1993a, 1993b, Thorburn and Walker, 1993; Dawson and Ehleringer, 1991; Ehleringer et al., 1991; White et al., 1985). Chimner and Cooper (2004) examined the stable isotopes of native desert shrubs to determine the plant water sources in the San Luis Valley, CO. They investigated the stable oxygen isotopes in precipitation, soil water from multiple depths, groundwater and plant xylem tissue to identify the water source for the primary shrubs in the valley. Chimner and Cooper (2004) were able to determine with stable isotopes that shifts in water uptake of phreatophytic shrubs (greasewood and rabbitbrush) from the unsaturated zone to groundwater was due to seasonal variations in soil water storage and precipitation.

Isotopic fractionation of hydrogen has been documented in halophytic plant species due to root discrimination of deuterium (δD) (Lin and Sternberg, 1993, 1994; Sternberg and Swart, 1987) therefore more reliance has been placed on the isotopic data obtained from the analysis of Oxygen-18 ($\delta^{18}O$). In this study, both δD and $\delta^{18}O$ were collected, but only the $\delta^{18}O$ data are reported.

This study brings all the aforementioned research approaches together to quantify the contribution of plant specific transpiration to overall ET. The previously mentioned publications

provide methods that have been incorporated into this study to provide a more comprehensive understanding of the complex interactions between plant species and water partitioning.

CHAPTER 3 METHODOLOGY

The study was conducted in central Spring Valley, NV in the Great Basin and is situated in the general location of the elevational transect of the Desert Research Institute Spring Valley 6 (SV6) site (Easting: 717823.99, Northing: 4324555.44, - Elevation: 1,755.71 meters (m)); this site was part of a prior study to measure ET within the Spring Valley phreatophyte zone. The soil type and textures at this site consisted of loam in the upper 40 centimeters (cm), sandy clay loam 40 cm-80 cm then transitioning to clay at a depth of 340 cm where no further soil samples were collected. This site was selected based on soil type and texture, canopy type (mixed stand), and existence of usable datasets for ET. However, due to screening issues related to the monitoring well at SV6, diurnal fluctuations in the water table were omitted for calculation of water use by phreatophytic vegetation due to non-discernable peaks and troughs. Instead, a combination of plant data combined with NDVI, soil moisture data, hydrologic balance in the upper meter of soil, and stable isotope data were compared to eddy covariance data obtained from the SV6 site to determine ET estimates and water source for plant use.

A plant assessment of four 25 m by 25 m plots was conducted at the SV6 site to determine the plant composition. All plants within each plot were counted and measured for height and two canopy diameters were taken in a perpendicular fashion. The area of an ellipse was used to estimate plant canopy areas at the site. The site consisted of 45% vegetative cover with 38% living cover and 7% consisting of dead material. The dominant species at the site were *Artemisia tridentata* with 71.3% of the canopy cover, followed by *Sarcobatus vermiculatus* at 19.2%, *Atriplex confertifolia* at 7.9%, and *Crysothamnus nauseosus* at 1.6% of the total vegetative cover (Table 1).

Table 1: Species present at each site, percent vegetative cover by species, percent living cover and total percent vegetative cover for Spring Valley 6 (SV6) EC tower site location (25m x 25m).

Site	Species	Scientific Name	Percent of Vegetative Cover	Percent Living Vegetative Cover	Total Percent All Vegetative Cover
SV6	Greasewood	<i>Sarcobatus vermiculatus</i>	19.2	17.4	45.4
SV6	Sagebrush	<i>Artemisia tridentata</i>	71.3	56.6	
SV6	Rabbitbrush	<i>Chrysothamnus nauseosus</i>	1.6	1.3	
SV6	Shadscale	<i>Atriplex confertifolia</i>	7.9	7.0	
SV6	Annuals		-	-	
SV6	Grass		-	-	

At the end of the growing season, all study plants were harvested. Also, a section of stem was collected from a branch on each shrub to calculate the conductive tissue area. The stem samples were wrapped in parafilm on both ends to prevent water from escaping the xylem tissue. All plant and stem samples were kept at 4 °C until all whole plant samples were photographed and sub samples of leaves could be collected for calculating leaf area. All whole plant samples were initially photographed from above on a white background prior to any processing as a secondary method to calculate leaf area. This was done within the first five days of collection. All fresh leaf sub-samples were collected within ten days of the conclusion of the study and all stem samples were processed within one month of the conclusion of the study. Fresh sub-samples of each study plant were collected, weighed and photographed and the whole plants and sub samples were dried, harvested, and weighed for calculating leaf area.

Leaf area was calculated by collecting sub-samples of fresh leaves from selected stems. All fresh sub-samples were arranged on a lighted background and photographed. This created a black and white contrast between the fresh leaves and the lighted background and eliminated the shadowing effects caused by photographing from above perpendicular to the photographed surface. The sub-samples were then dried, re-weighed, and re-photographed using the same

technique to provide a fresh weight and dry weight area of all plants, providing a means to upscale the leaf area to the whole plant level.

To calculate the area of conductive tissue area for each species, a dye study was performed to not only determine the area of conductive vascular tissue, but also the patterns of flow in each species. The conductive vascular tissue of the stems was stained using 1 gram (g) of safranin dissolved in 40 milliliters (mL) ethyl alcohol and brought to a final volume of 1000 mL with distilled water. Airtight tubing was attached to each end of the stem and the dye was pulled through the bottom of the stem using suction. This resulted in staining of only the conductive tissue. A trial of this technique was performed on stems collected from each species at SV6. All stems were cut in a 4 °C cold room, however two were cut on a bench and two were cut underwater to assess the possibility of cavitation. Both the bench top and the underwater method showed species-specific patterns of flow that were mainly characterized by strong pink bands located on the outer area of the stem, indicating flow was mainly concentrated along the outer lobes of the stem. Although both the underwater and bench top cutting methods resulted in similar staining outcomes, the decision was made to continue cutting the stems under water to reduce the chance of cavitation.

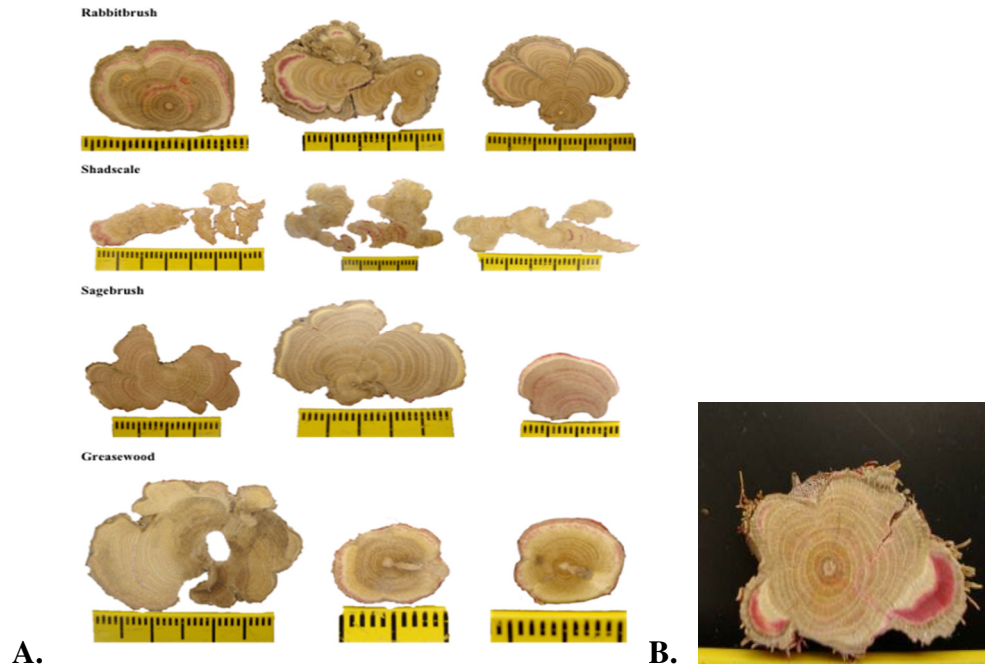


Figure 1: Photo A depicts representative samples used for the dye study from each species while photo B represents a more detailed view of a sagebrush sample stained with safranin using the dye study technique.

Cross sectional area was assessed and conductive tissue area of each stem cutting using a Canon 7D digital camera was mounted to a stand such that the camera was perpendicular to the shooting surface. A standard with a known area of 10 cm² and a metric ruler were placed adjacent to the stem cutting so each photograph could be properly calibrated using Photoshop CS5 software (2010) to accurately assess the area of each stem. Every stem was photographed and the untouched photographs were imported into Photoshop CS5. Area of the stem was calculated by highlighting the perimeter of the stem using the wand tool in Photoshop CS5 and selecting 'calculate area.' Any bark material was excluded from this calculation. The sap flow area was calculated by isolating the pink area from the rest of the plant stem tissue in each photograph. In the rabbitbrush and sagebrush, there was some lateral dye movement within the dead material of the stem and this was excluded from the sap area calculations based on laboratory tests that isolated the inner cortical tissue using a rubber sealant.

Soil samples were collected in close proximity to each species throughout the study for soil water content, salinity, isotopic analysis, and chloride analysis. Soil samples at various depths were collected using a hand auger and samples were placed into soil bags, sealed tightly, and placed on ice and transported to the lab where all samples were placed in a 4 °C walk-in cold room. Within 48 hours, a subsample, approximately 25 g, of soil was taken for gravimetric water content. Each sample was initially weighed, dried in an oven at 105 °C for 48 hours, and reweighed to determine water content of the soil. Sub-samples were also taken for cryogenic distillation for isotopic analysis (procedure below). All remaining soil from each sample was dried in a greenhouse for approximately two weeks to ensure a fully air dried status.

To determine salinity and chloride content of the soils, a saturation extract was performed on all dried soil samples. Approximately 100 g of dried soil was weighed, saturated with distilled water, and allowed to sit in a closed container for 24 hours to allow salts to solubilize into solution. The soils were then placed on filter paper within a Buchner funnel and water was pulled through the funnel under tension to extract the soil water for chemical analysis.

A conductivity bridge (Beckman Industrial model RC20) was used to determine the salinity of the soil solution. Prior to each use, the conductivity bridge was calibrated using room temperature (22-26 °C) 0.01 mole potassium chloride (KCl). Temperature and electrical conductivity (ECe) was measured on each sample. Drift in the response of the KCl standard was always under five percent. After calibration, the pipette and electrodes were rinsed thoroughly with deionized water and then rinsed with the new sample prior to recording the ECe value in decisiemens per meter (dSm^{-1}).

A chloridometer was used to determine the chloride concentration of the saturation extract. The chloridometer was initially calibrated using four vials of chloridometer reagent. Then a

standard curve was determined by preparing five vials of chloridometer reagent of varied concentrations (1 milliequivalents/liter [meq/L], 5 meq/L, 25 meq/L, 50 meq/L, and 100 meq/L).

Isotopic water samples for determining the water source of the shrubs were collected using several different methods. Isotopic composition of soil water was accomplished through cryogenic distillation. Soil samples were collected from various depths throughout the course of the study to develop an isotopic profile of soil moisture and aid in determining the plant water source. Water and soil samples were immediately placed on ice and kept at 4 °C until processing was completed. 100-150 g of soil was placed in a flask and attached to a closed system cryogenic trap. The trap glassware was placed inside a dewer canister containing dry ice to immediately freeze any water vapor transferred into the trap system for isotopic analysis (Figure 2). Soil within a glass reservoir connected to the cryogenic trap system was heated in an oil bath to 100 °C to drive water vapor from the soil into the cryogenic trap. This was done until all the soil water was driven from the soil into the trap to minimize isotopic fractionation. This process typically took approximately two hours per sample and was verified by weighing the samples before and after the distillation process. In all cases the samples reached oven dried status.

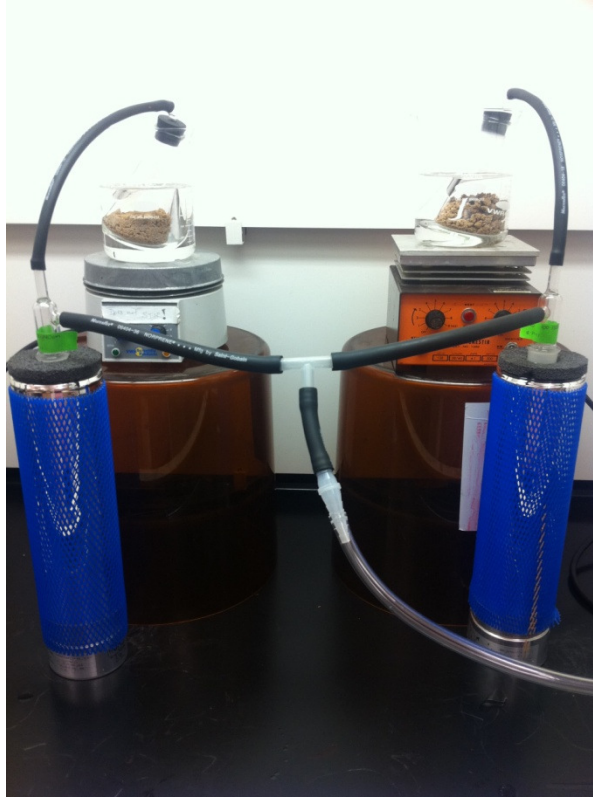


Figure 2: Cryogenic trap system used for distillation of soil water for isotopic sampling.

Well water samples were collected for isotopic analysis from an on-site well screened across the groundwater table. A gasoline powered pump was used and several pore volumes were cleared before a representative groundwater sample was collected to ensure the water collected was representative of current groundwater conditions.

Water samples collected for isotopic analysis, except xylem tissue samples, were analyzed at the Las Vegas Isotope Science Laboratory (University of Nevada, Las Vegas) on a Thermo Electron high-temperature thermal conversion elemental analyzer (TC/EA) in continuous flow mode with ultra-high purity helium, coupled to a Delta V Plus isotope ratio mass spectrometer. The samples were reacted at 1450 °C in a glassy carbon tube connected to a reverse-flow helium adaptor, and the resultant hydrogen(H_2) and carbon monoxide (CO) gases were separated on a GC column at 95 °C prior to delivery to the mass spectrometer (Gere et al., 2004). Data were

calibrated on international and internal standards including Vienna Standard Mean Ocean Water (VSMOW), Greenland Ice Sheet Precipitation, and Standard light Antarctic Precipitation (SLAP). The data were calibrated such that the values for VSMOW were $\delta D = 0$, $\delta^{18}O = 0.0$, and SLAP $\delta D = -428$ and $\delta^{18}O = -55.5$ ‰, respectively. Resulting precision for δD and $\delta^{18}O$ was better than 2.0 and 0.20 ‰, respectively (Lachniet 2011, personal communication).

Xylem water extraction was performed on mature stem samples from each species. Parafilm was placed on each end of the stem to preserve the water within the xylem tissue and the samples were placed in sealed containers and packed on ice. Refrigerated samples were sent to the University of Utah (Salt Lake City, UT) within 24 hours of sample collection for extraction and analysis of xylem water isotopic composition. The University of Utah utilized cryogenic vacuum distillation to extract xylem exudate. Water was evaporated from the stem samples under vacuum and condensed into a collection tube to at least 98% completion to prevent isotopic fractionation (West et al., 2006). The collected water samples were then analyzed for isotopic composition by using Wavelength-Scanned Cavity Ring-Down Spectroscopy (WS-CRDS) technology (Picarro Instruments) where absorption spectroscopy, using an infrared laser, determines the isotopic composition of the water sample with a precision of 1.0 per mil for δD and 0.2 per mil for $\delta^{18}O$ (Gupta et al., 2009; Lis et al., 2008).

Several different midday (11:00am – 2:00pm) soil and plant measurements were collected bi-monthly to monitor and assess conditions at the site throughout the growing season and all measurements were done in triplicate for statistical analysis. For each plant in the study, a digital anemometer (SPER model 840032) was used to collect ambient air temperature (T_A) near each plant and an infrared thermometer (Cole Palmer model 39800) was used to measure temperatures for the plant canopy (T_C), soil temperature underneath the canopy and temperature of the bare

soil. Temperatures between the plant canopy and the ambient air temperature were calculated ($T_C - T_A$).

A chlorophyll index meter (Spectrum Technologies model CM1000) was used to indirectly assess the chlorophyll content for the canopy of each plant. The chlorophyll index meter detects the reflection of light at 700 nanometers (nm) and at 840 nm to calculate a chlorophyll index value (between 0 and 999). Chlorophyll absorbs light at the 700 nm wavelength which reduces the reflectance of the 700 nm wavelength from the leaf surface. Light at 840 nm wavelength is not absorbed by chlorophyll therefore serves as an indication of how much light is reflected due to physical leaf characteristics such as the presence of a hairy leaf surface or a waxy coating. A chlorophyll index value is calculated from the measured ambient and reflected light data. An ambient light sensor measures ambient light and displays a brightness index value ranging from 0 – 9. At low levels of ambient light, the chlorophyll index reading may result in error. Higher light levels enable greater resolution in the chlorophyll content. Measurements were only collected when the ambient light level was above 4 to eliminate error due to low light (Spectrum Technologies Operation Manual).

A Steady State Porometer (Li-Cor model LI-1600) was used to measure stomatal conductance for each species at the beginning and end of the growing period (June 2009, August 2009, and September 2009). Leaves were selected from surrounding non-study plants of the same species within SV6 and data was collected in triplicate for statistical analysis. Each leaf sample was clamped into place on the porometer's sensor head and measurements for leaf temperature, relative humidity, stomatal conductance, and transpiration were obtained.

A Pressure Chamber Instrument (PMS Instrument Company model 1000) was used to measure mid-day xylem water potential on a monthly basis throughout the growing season. To

determine the xylem water potential for each species, a small mature stem was cut from a non-study plant and the stem was inserted into the compression aperture on the pressure chamber with the cut end facing upwards. Nitrogen gas was then slowly released into the chamber. The stem was viewed from above through an ocular lens to observe the point when water was forced back up from the xylem to the cut surface, noting the pressure required. This pressure, reported in megapascals (MPa), represented the equal but opposite tension in the xylem the leaves were experiencing at the time of cutting.

A Profiler Probe (Delta-T model PR2/6) was used to measure soil moisture content at different depth intervals within the soil profile. The profiler probe consists of a sealed polycarbonate rod approximately 25 mm in diameter, with electronic sensors arranged at fixed intervals along its length. The probe was inserted into access tubes that were installed to a depth of 100 cm at locations throughout the SV6 site. The access tubes were constructed of a specially designed thin-wall material, which maximizes the penetration of the electromagnetic field into the surrounding soil. At the SV6 site, there were five separate locations where access tubes were placed for monitoring soil moisture changes which included one adjacent to each of the four species on site and one in bare soil. However, dieback of several of the greasewood plants occurred due to insect damage, a sixth access tube was placed underneath a living healthy greasewood plant and readings were collected from both the new access tube and the old access tube.

An LAI Ceptometer (AcuPAR model LP-80) was used to measure the Leaf Area Index (LAI) for individual shrubs within the plant canopy. The AcuPAR ceptometer measures photosynthetically active radiation (PAR) as it passes through the canopy using 80 independent photosensors, spaced 1 cm apart, within the 400-700 nm waveband which represents the portion

of the spectrum where photosynthesis occurs. Three measurements were taken underneath each study shrub monthly. LAI was calculated with an internal data processor and stored in predesignated files.

Five ground based NDVI sensors were installed at the SV6 site to monitor phenological changes throughout the growing period, including green-up and senescence events. The ground based dual channel SKR-1800 radiometer sensors (Skye instruments LTD, Powys, UK) used at this site were customized to collect data in two different broadband channels: channel 1: 630-690 nm (red) and channel 2: 760-900 nm (NIR). The two sensors simultaneously measured incident solar radiation (channel 1) and upward reflectance (channel 2) and maintained a field of view of 25°, standard for this instrumentation which was suitable for tracking phenological changes at this site. Sensors were mounted along horizontal beams attached to vertical steel poles with the incident sensor positioned upwards and the reflectance sensors placed over a single representative of each study species including *Sarcobatus vermiculatus*, *Crysothamnus nauseosus*, *Artemisia tridentata*, and *Atriplex confertifolia* and one sensor positioned over bare soil. Two different incident sensors were attached adjacent to each other because a combination of old and new sensors were used at the SV6 site. The new sensors were not compatible with existing equipment so a separate incident sensor was installed to correct for the compatibility issue. A CR10X datalogger collected data in thirty-minute averages and data was stored to SM4M and SM16M storage modules and downloaded on a bi-monthly basis. All the downloaded data were processed in the lab and the NDVI values were calculated as follows:

$$\text{NDVI} = \frac{(Z * \text{NIR}_{\text{R(nA)}} * Y) - (\text{Red}_{\text{R(nA)}} * X)}{(Z * \text{NIR}_{\text{R(nA)}} * Y) + (\text{Red}_{\text{R(nA)}} * X)} \quad (\text{Equation 1})$$

Where:

X: NIR_I incident reading (μmol s⁻¹ m⁻²)

Y: Red_I incident reading (μmol s⁻¹ m⁻²)

Z: Ratio sensitivity of reflected NIR: Red

NIR_{R(nA)}: Reflected reading in nanoamps

Red_{R(nA)}: Reflected reading in nanoamps

A fully equipped eddy covariance flux tower (Campbell Scientific Inc, Logan UT, USA) was previously installed at the SV6 site (Figure 3). The EC tower was mounted to a galvanized steel tripod and sensors were installed 1m above the canopy surface. A 3D sonic anemometer (CSAT-3, Campbell Scientific Inc. Logan, UT, USA) and an open-path infrared gas analyzer (IRGA, Li-Cor 7500, Li-Cor Inc, Lincoln NE, USA), a net radiometer (REBS net radiometer), soil heat flux plates (Model HFP01SC), and two soil thermocouple probes (model TCAV-L) were installed at the SV6 site. Soil sensors were installed in the upper 20 cm. Precipitation was measured using a standard bulk rain and snow gauge (2.5 m above ground surface) and was attached to the eddy covariance tower. Data were collected in 30 minute averages and were recorded with a data logger (CR5000, Campbell Scientific) and stored on a compact flash card for post-processing. Data from SV6 were downloaded monthly when instruments were checked and maintained. Eddy covariance data were provided and processed by Desert Research Institute (Las Vegas, NV).



Figure 3: Fully equipped eddy covariance flux tower installed at SV6 site.

The basin is considered a mostly closed system, therefore ET is believed to account for a majority of the basin discharge (Devitt et al., 2010; Conrad, 2008). Water use characteristics for each shrub species were investigated through a water balance closure technique (Equation 2):

$$\mathbf{ET = I - O - \Delta S} \qquad \qquad \qquad \mathbf{(Equation\ 2)}$$

Where ET is evapotranspiration, I is the input from precipitation and snow melt, O is the output from drainage and runoff, and ΔS is the change of water storage.

Data were analyzed using descriptive and/or linear and multiple regression analyses. Multiple regressions were performed in a backward stepwise manner with deletion of terms occurring when p-values for the t-test exceeded 0.05. To eliminate the potential for co-correlation, parameters were only included if variance inflation factors were < 2 and the sum total was < 10 . All statistical analyses were performed using SigmaPlot 11.0 and SigmaPlot 13.0 Software (Systat Software, Inc., Point Richmond, CA).

CHAPTER 4 FINDINGS OF THIS STUDY

SV6 Site Description

Research was conducted in central Spring Valley, which is within the Great Basin region of NV. The site was situated within the Nevada System of Higher Education's climate change monitoring network known as NevCAN (Nevada Climate-ecohydrological Assessment Network) (Northing: 4324555.44, Easting: 717823.99 - Elevation: 1,755.71 meters). The site contained a mixed stand of both phreatophytic and non-phreatophytic vegetation with soil consisting of loam/clay loam in the upper 40 cm, sandy clay loam 40cm-80cm then transitioning to clay to a depth of 340 cm (Table 1). The total precipitation during the experimental sampling period (March 1, 2010 – September 23, 2010) was 8.91 cm and the total ET during this period was estimated at 22.6 cm using the eddy covariance (EC) technique (Table 2). The total ET exceeded the precipitation received during the study period indicating water use of stored soil moisture from winter recharge along with groundwater extraction by phreatophytic vegetation at the site was most likely occurring.

Table 2: Monthly values for precipitation, evapotranspiration (ET) Potential ET (ET_o), and the maximum and minimum temperatures for the SV6 site for the 2010 sampling period.

Month	Precipitation (cm)	ET (cm)	ET-Precipitation (cm)	ET_o (cm)	Max Temp (°C)	Min Temp (°C)
April	3.05	3.44	0.39	17.7	21.8	-18.5
May	2.79	5.62	2.82	16.1	24.6	-6.7
June	0.03	3.93	3.90	21.2	33.7	-4.9
July	2.62	4.71	2.09	23.0	36.4	-0.2
August	0.43	3.05	2.62	21.3	33.6	-0.0
September	0.00	1.88	1.88	17.7	32.1	-5.1
TOTALS	8.92	22.63	13.71	-	-	-

Plant Size and Biomass

Plant size and biomass varied for each species but distinct trends were observed that were non species specific. Table 3 depicts the leaf area (cm²), leaf biomass (g), canopy volume (cm³), leaf area/canopy volume (cm²/cm³), trunk area, and percent conductive tissue for each species. Plant data suggested that as the leaf area increased the leaf biomass increased in a linear fashion for all species ($R^2=0.95$, $p<0.0001$). The percent of conductive tissue for smaller stems was much greater than for larger stems when all species were combined and evaluated ($y = 5.0555 + (4.3639/\text{Area}) + (9.7451/\text{Area}^2)$, $R^2=0.44$, $p<0.0001$). Leaf area divided by canopy volume varied by species. For sagebrush, values between 0.251 to 0.307 cm²/cm³ were observed. Shadscale values were lower with values ranging between 0.115 to 0.142 cm²/cm³. Rabbitbrush maintained the lowest values for leaf area per canopy volume with values ranging from 0.014 to 0.021 cm²/cm³. Due to significant insect damage to the greasewood during the experimental period, only a single value of 0.078 was recorded. This data indicates that sagebrush contained more leaf area per canopy volume than any other species at the SV6 site, a significant driving force for ET in the mixed shrubland plant community.

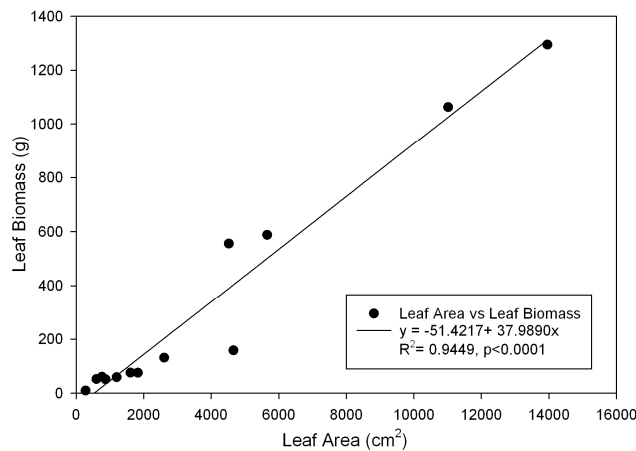


Figure 4: Leaf surface area vs. leaf biomass at the SV6 site.

Table 3: Leaf area, leaf biomass, canopy volume, leaf area/canopy volume, trunk area and percent conductive tissue for each species.

Plant	Leaf Area (LA) (cm ²)	Leaf Biomass (g)	Canopy Volume (cm ³)	LA/Canopy Volume (cm ² /cm ³)	Trunk area (cm ²)	% Conductive Tissue
Sagebrush 1	1825	75.43	6465	0.282	117.35	3.18
Sagebrush 2	2605	130.84	8478	0.307	69.77	9.78
Sagebrush 3	4657	158.35	18569	0.251	126.81	5.5**
Greasewood 3	4521	555.68	58259	0.078	29.49	11.22
Greasewood 4	13960	1294.88	-	-	-	25.22*
Greasewood 5	5656	587.79	-	-	-	15.77*
Greasewood 6	600	52.31	-	-	-	-
Rabbitbrush 1	11018	1063***	765167	0.014	133.51	8.52**
Rabbitbrush 2	278	9.49	12953	0.021	27.25	5.82**
Rabbitbrush 3	1197	59.09	57207	0.021	38.40	6.63**
Shadscale 1	1608	75.75	11304	0.142	41.93	7.37
Shadscale 2	868	51.32	7545	0.115	32.99	12.40**
Shadscale 3	763	60.68	6506	0.117	13.36	15.34

* Plants added later in the study due to insect damage to original plants. Trunk measurements unavailable.

** Average conductive tissue area of two separate stems for the same plant

*** Predicted value based on regression analysis

Groundwater Assessment

Groundwater at the SV6 site exhibited recharge through late May of 2010 before showing a sharp decline with the onset of warm summer temperatures through mid-October 2010 (Figure 5). The 0.5 m decline in groundwater levels corresponded to the growing period of the phreatophyte greasewood. The groundwater extraction by plants declined in October relative to recharge, leading to inversed groundwater levels.

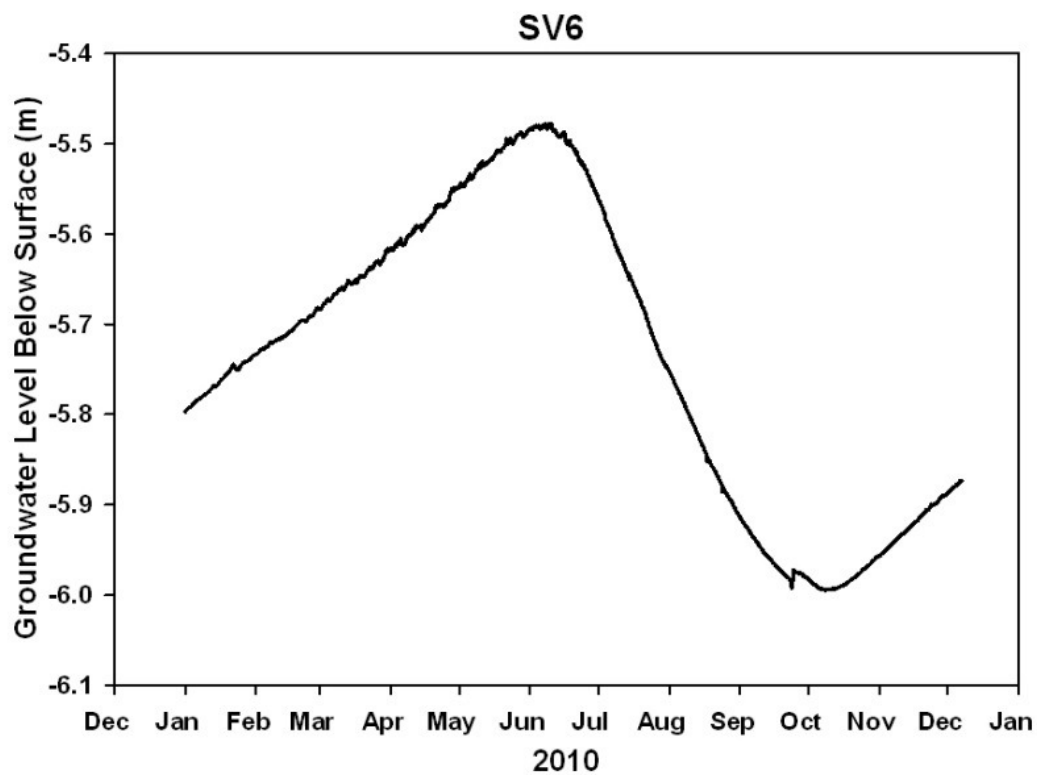


Figure 5: 2010 groundwater levels at the SV6 site.

Soil Moisture Assessment

Soil water content with depth was used to assess shifts in soil water in storage over time and to provide assessments of evapotranspiration. Changes in soil water content varied with each species, with greatest changes occurring near the surface and as temperature and environmental demand increased (Figure 6).

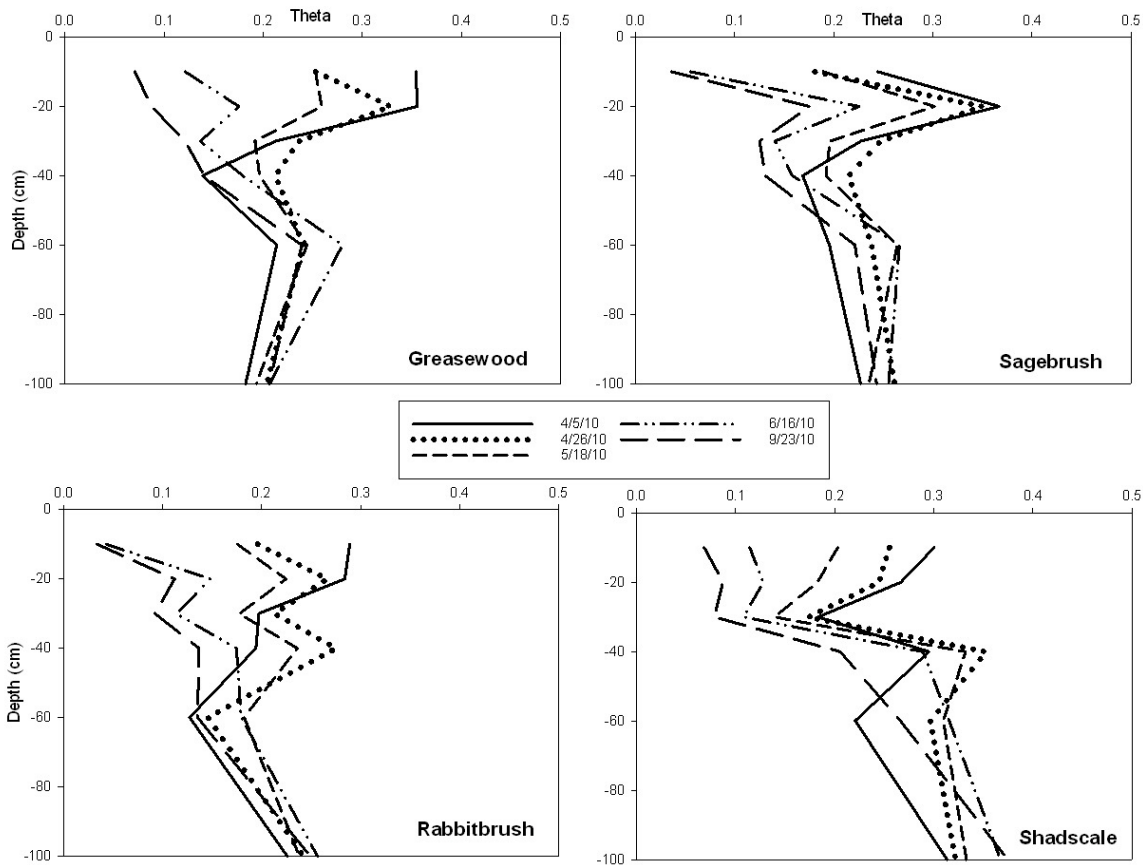


Figure 6: Change in soil volumetric water content (θ) for each species throughout the growing period between 0-100 cm.

Greasewood plants showed declines in soil water storage down to the 40 cm depth, indicating root water extraction occurring in this shallow region recharged by precipitation, (April $\theta = 0.21 - 0.33$, June $\theta = 0.12 - 0.18$). Rabbitbrush also showed a strong decline in soil water content but to depths as great as 60 cm (April $\theta = 1.9 - 2.9$, June $\theta = 0.08 - 0.17$). Whereas shadscale

showed a steady decline in soil water content throughout the entire growing period but appeared restricted to the upper 30 cm (April $\theta = 0.18 - 0.30$, September $\theta = 0.06 - 0.07$), while sagebrush showed soil moisture depletion to the 40 cm depth (April $\theta = 0.20 - 0.25$, September $\theta = 0.04 - 0.13$). Bare soil revealed similar soil water depletion patterns as observed with the plants over the upper 40 cm, suggesting possible encroachment of roots from surrounding vegetation leading to water extraction (April $\theta = 0.21 - 0.24$, September $\theta = 0.06 - 0.15$).

Soil water in storage was assessed during the monitoring period by weighting soil volumetric water contents over specified depth increments based on a one m² area. These storage amounts (cm) are reported for all four species over time (Figure 7). In the 0 – 15 cm region, there was a steady decrease in soil water in storage ranging from 3.7 – 5.3 cm in early April to 0.7 – 1.7 cm in mid-June. This depletion reflected plant water uptake and evaporation in the upper 15 cm, with storage values remaining between 0.6 – 1.1 cm with little change throughout the rest of the summer and fall monitoring period. This same downward trend occurred in the 15 – 25 cm and 25 – 35 cm regions but was more gradual than observed in the 0 – 15 cm region. Storage values in the 15 – 25 cm region declined from 2.7 – 3.6 cm in April to 1.1 – 2.1 cm in July. Whereas in the 25 – 35 cm region values declined from approximately 2.7 – 3.7 cm to 0.9 – 1.4 cm, with no visible separation between species. In the 35-50 cm region, storage values increased over the first few weeks of monitoring, with the exception of sagebrush, reflecting soil water recharge from 2.5 – 3.1 cm in April then returning to declining values. However, by May storage values for all species began to show a slight decline with higher overall storage values under shadscale than the other 3 species. The fact that storage values did not increase under sagebrush in this region (2.0 – 3.1 cm) would suggest that the upper 50 cm was an active zone for sagebrush water extraction. Whereas the higher values under shadscale (3.1 – 4.4 cm) would suggest that lower

plant water extraction was occurring by this species in this zone compared to the other species. In the 50-80 cm zone, soil water in storage increased during the period of April to early June, indicating that deep recharge was occurring in this zone under all four species. However, there was a distinct separation in the amount in storage for rabbitbrush at this depth revealing storage values between 3.8 and 5.5 cm compared to the other three species which had soil water in storage values between 5.9 and 9.5 cm, suggesting that rabbitbrush was accessing this deeper soil water to a greater extent. Finally, in the 80 – 120 cm zone, greasewood, sagebrush, and rabbitbrush all revealed a very gradual increase in soil water storage over the growing period, whereas shadscale storage values increased from 12.5 cm in early April to 16.4 cm in late August. This continued buildup in soil water in storage at this deeper depth, suggested that recharge was occurring to a greater extent than plant water extraction in this zone, with greasewood having the lowest storage values of all four species.

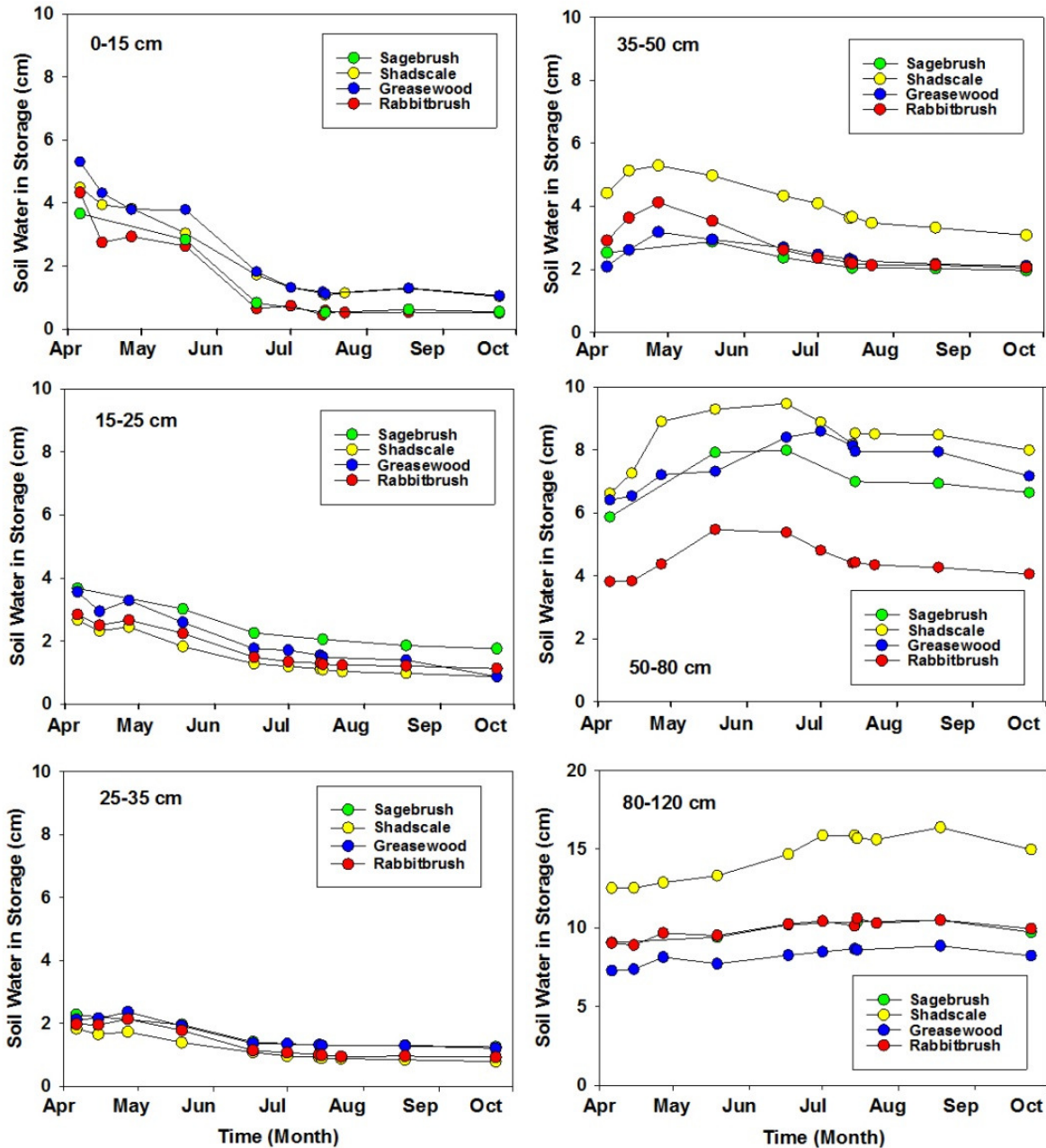


Figure 7: Soil water in storage at varying depths from 0 to 120 cm for SV6 site.

All species showed a similar trend in relative storage through middle May with relative storage increasing for all species in April from 0.94 – 1.00 cm to 1.04 – 1.08 cm then began to steadily decline for all species through mid-May (Figure 8). Rabbitbrush and shadscale began to diverge in mid-May with rabbitbrush showing a faster and higher depletion in relative storage

declining from 1.04 cm to 0.86 cm in June and continuing to reduce the amount of water in relative storage through October to 0.75 cm suggesting that rabbitbrush is utilizing more water in storage than the other species in the upper 100 cm. Shadscale showed the least amount of reduction in relative storage change with values that declined from 1.03 cm in May to 0.94 cm in June then to a maximum decline in September of 0.88 cm suggesting this species is utilizing the least amount of water available in storage. Greasewood and sagebrush showed similar trends where both species showed recharge at the beginning in May (greasewood from 0.98 – 1.04 and sagebrush from 1.03 – 1.09 cm) then declined down to 0.89 cm for both species before declining to 0.77 cm in September for greasewood and 0.81 cm for sagebrush. This suggested that these species are extracting soil water in storage similarly in the upper 100 cm.

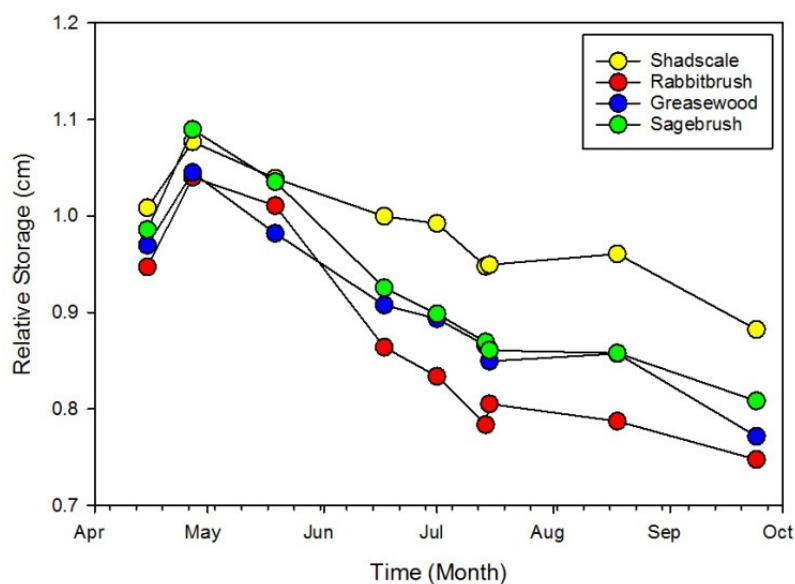


Figure 8: Total change in relative soil water storage (cm) for each species between 0-100 cm throughout the growing period at the SV6 site.

Water Balance Assessment

A water balance technique was used to determine species specific ET contribution. Water balance was calculated using the method of $ET = \text{Precipitation} - \text{Drainage} - \text{Change in Storage}$

where drainage was assumed to be zero due to the concept that the basins are believed to be mostly closed, therefore ET accounts for the majority of basin discharge (Devitt et al. 2008). The derived values were then weighted against the percentage of living vegetative cover to determine the canopy ET contribution for each species. The bare soil component was assumed to contribute to the canopy ET due to the fact that the bare soil component contained extensive rooting systems beneath the soil from neighboring vegetation that were not visible on the surface contributing to the uptake of soil moisture. To determine the value of evaporation of bare soil, the percentage of bare soil, 54.6% (Table 1) of the total cover at the SV6 site, was multiplied by the total precipitation received to derive a value of 4.87 cm which was used to account for the bare soil evaporation component. The combined bare soil evaporation component with the overall vegetative ET component (45.4%, Table 1) totaled 16.09 cm. The eddy covariance ET (ET_{EC}) values for the SV6 site during the sampling period totaled 22.63 cm (Table 2) with the canopy and bare soil ET accounting for 16.09 cm suggesting that 6.54 cm (Table 4) ET_{EC} remained. This suggests the remaining ET_{EC} is most likely due to groundwater contribution to the overall ET_{EC} from phreatophytic vegetation.

Table 4: Water balance ET values for each species, total vegetative cover ET, bare soil ET, and possible groundwater contribution to ET.

Species	ET weighted (cm)
Sagebrush	7.63
Greasewood	2.64
Shadscale	0.77
Rabbitbrush	0.20
Total ET Vegetation (cm)	Total ET Bare Soil (cm)
11.22	4.87
Potential Groundwater ET contribution (cm)	
6.53	

Soil Salinity and Chloride Analysis

Data for the electrical conductivity of soils (saturation extracts, ECe) collected at SV6 between the 0-340 cm depth revealed that soils were highly saline with salinity buildup peaking in the 140-180 cm depth region. However, at shallow depths (0-40 cm) soil salinity levels were below 4 dSm^{-1} , a level used to classify soils as saline (United States Salinity Laboratory, 1954). Beyond this upper region, salinity levels steadily increased to values in the saturation extract to over 30 dSm^{-1} , before declining (Figure 9) beyond the 180 cm depth. Chloride concentrations in the saturation extracts revealed similar patterns to salinity, with chloride concentrations between 0-200 meq/L in the upper 30 cm, followed by a steady increase to the 100 cm depth, peaking between 2000-8000 meq/L in the lower 100-340 cm depth region (Figure 10). The salinity and chloride data revealed a steady state profile over the upper soil region (100 cm for Cl, 140 cm for ECe). ECe with depth was highly linear ($R^2 = 0.775$, $p < 0.0001$) to a depth of 140 cm (Figure 11) and chloride concentration also revealed a highly linear relationship ($R^2 = 0.596$, $p < 0.0001$) to a depth of 120 cm (Figure 12) indicating that water extraction was declining with depth and that this pattern has been maintained for a significant period of time. Salinity values peaking at 30 dSm^{-1} in the saturation extract ($>50 \text{ dSm}^{-1}$ in the soil solution) would suggest that deep rooted non halophytic shrubs such as sagebrush would most likely not be able to extend roots through this barrier to access groundwater.

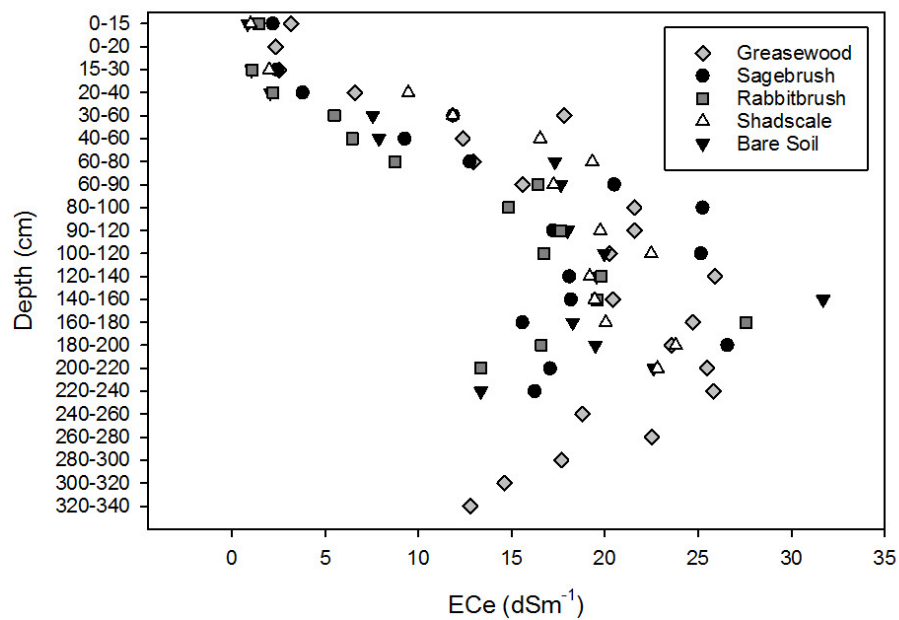


Figure 9: ECe (dSm⁻¹) for soils at varied depths between 0-340cm at SV6.

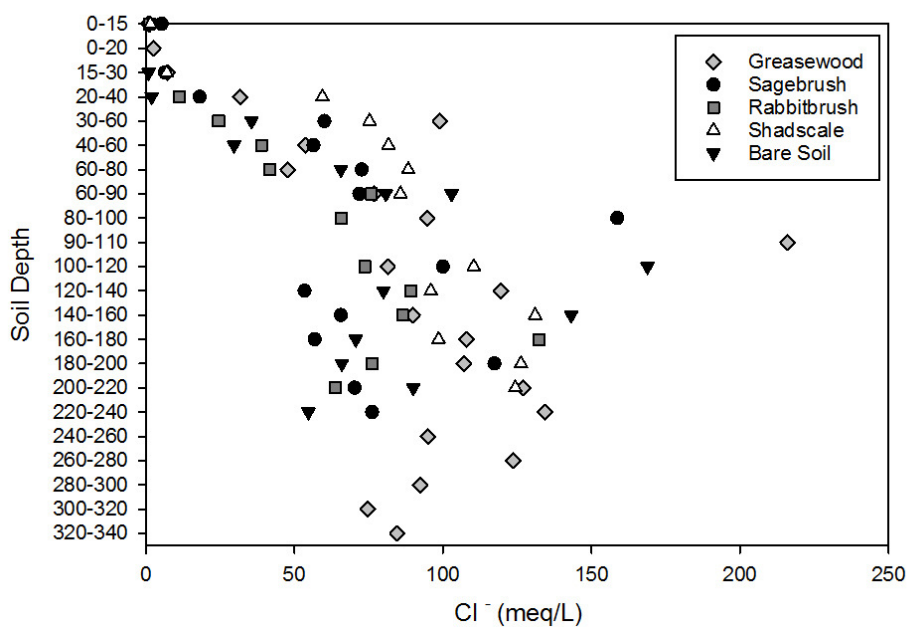


Figure 10: Chloride concentration (meq/L) at varied depths between 0-340cm.

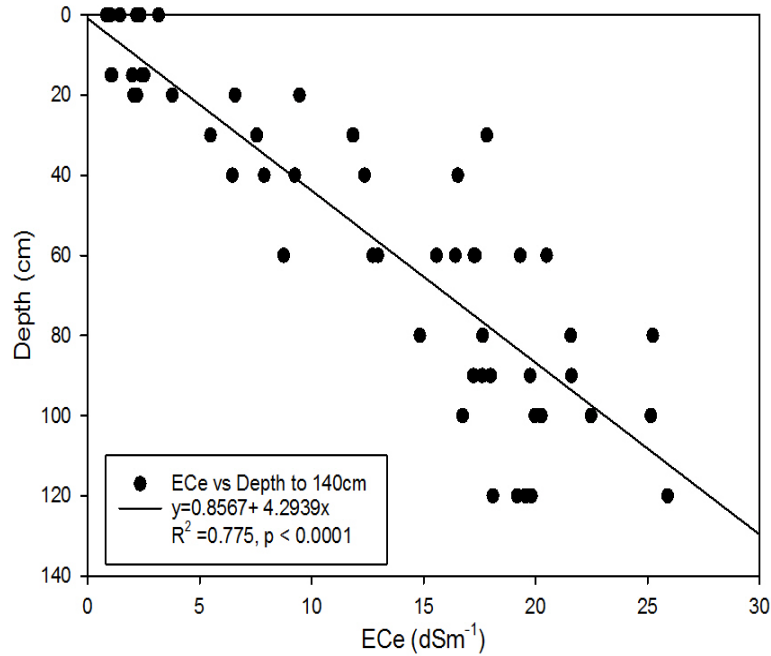


Figure 11: Regression analysis of the upper 140 cm for ECe for all species shows a linear increase ($R^2 = 0.775, p < 0.0001$) in salinity.

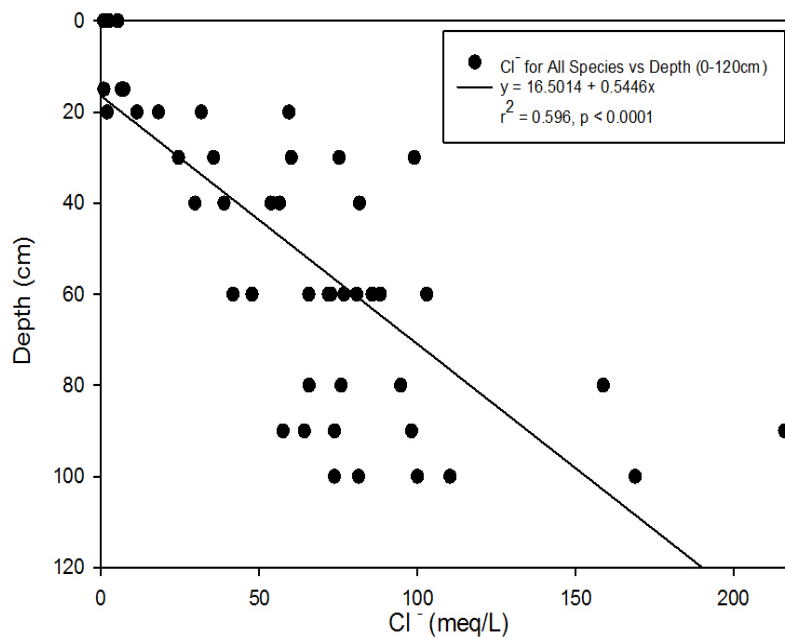


Figure 12: Regression analysis of the upper 120 cm for Cl⁻ for all species shows a linear increase ($R^2 = 0.596, p < 0.0001$) in chloride concentration.

Leaf Xylem Water Potential and Storage Depletion Response

Mid-day leaf xylem water potential, (ψ_L , MPa) was used to assess plant water status for the 2010 growing period (March – September). Storage depletion values were weighted with corresponding ECe values with depth to 100 cm for each species and then plotted with ψ_L values for each species from May to October 2010 (Figure 13).

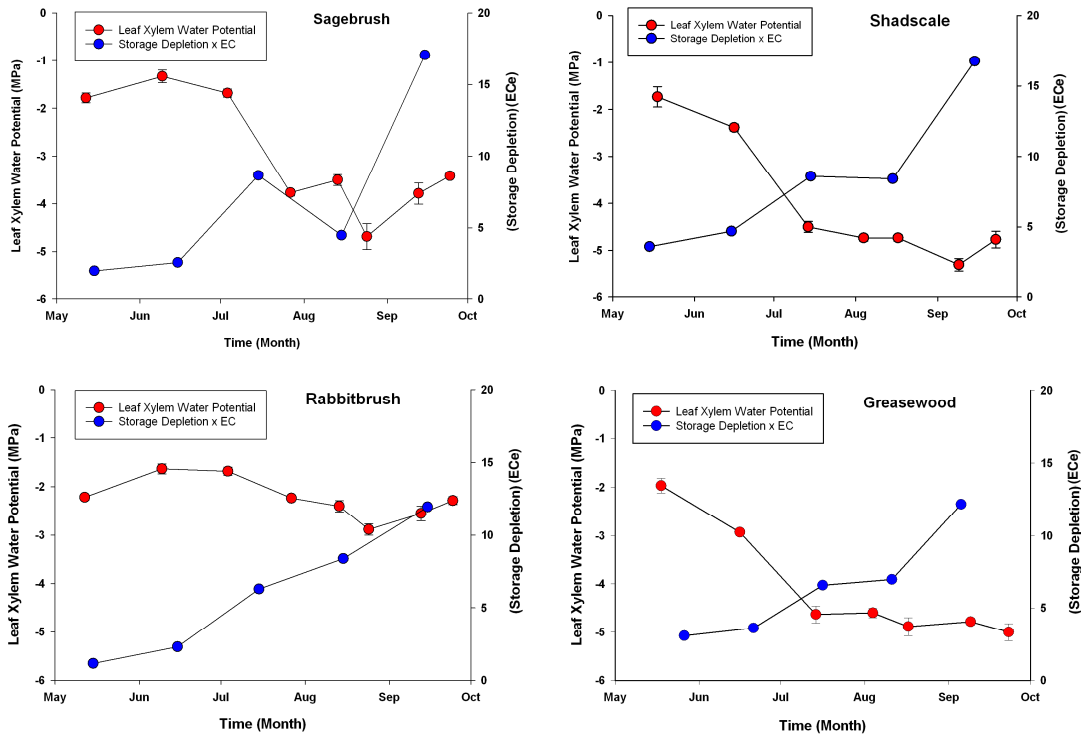


Figure 13: Mid-day leaf xylem water potential (ψ_L , MPa) with storage depletion weighted with ECe (dSm^{-1}) was used to assess species stress response the 2010 active growing period (May – October) for SV6.

ECe values were measured at the end of the monitoring period which revealed a steady state condition that was assumed would also be representative of the entire growing period.

Greasewood and shadscale, both halophytes, ψ_L values became more negative from May through mid-July with greasewood declining from ψ_L of -1.9 MPa in May to -4.6 MPa in mid-July, showing little change through September (ψ_L = -4.6 to -5.0 MPa) while soil moisture depletion

weighted with ECe increased from 3.0 to 12.1 suggesting greasewood was experiencing increased levels of stress by mid-summer as it lowered its internal xylem water potential to maintain more favorable water potential gradients. Shadscale showed the same trend as greasewood with initial ψ_L of -1.7 MPa in May and then declining to -4.5 MPa by mid-July with a continued slight downward trend through September (ψ_L = -4.7 to -5.3 MPa). Shadscale also showed the same trend as greasewood with increasing values of soil water storage depletion ECe reaching maximum values of 16.8 in September. Sagebrush maintained a more favorable ψ_L with a slight decrease in ψ_L from May to June (ψ_L = -1.8 to -1.3 MPa) before beginning to decline in response to increasing stress associated with soil water storage depletion ECe values increasing from 2.0 in May to 8.6 in July. Sagebrush showed a response to mid-summer precipitation in July with storage depletion ECe values declining to 4.5 with some recharge observed along with a slight increase in ψ_L from -3.8 MPa in July to -3.5 MPa in August before ψ_L returned to values between -3.4 MPa and -4.6 MPa as soil water depletion ECe increased to a maximum of 17.1 in September. Rabbitbrush showed little signs of water stress with ψ_L beginning to decline slightly in June (ψ_L = -1.7 MPa) through August where a maximum stress level of -2.9 MPa was observed before ψ_L began to increase through September (ψ_L = -2.3 MPa) while storage moisture depletion ECe values gradually increased throughout the growing period, indicating rabbitbrush was maintaining a more favorable plant water status throughout the growing period than the other three species. Rabbitbrush was clearly not responding to shifts in soil water depletion weighted with ECe in the upper 100 cm region. Such a response suggests that rabbitbrush was acquiring water from zones in the soil profile that the other species were not accessing as efficiently. Even greasewood, a known halophyte, responded to the soil water depletion ECe values, supporting a different strategy being employed by rabbitbrush.

Plant Response to Seasonal Stress

Temperature differential ($T_c - T_a$) between the canopy temperatures (T_c) and ambient temperature (T_a) was measured for each species on a monthly basis near solar noon for the duration of the growing period (Figure 14).

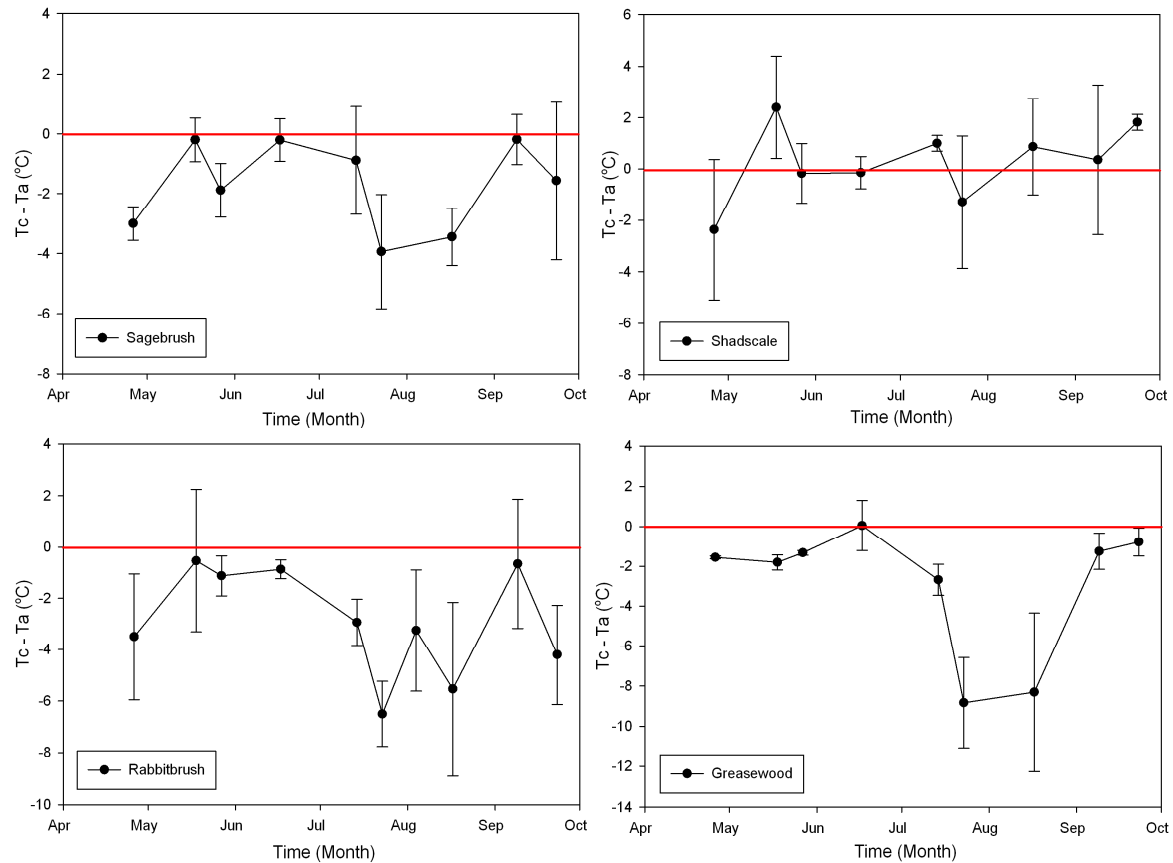


Figure 14: Temperature differential ($T_c - T_a$) between canopy temperatures (T_c) and ambient temperature (T_a) for all species at SV6 site.

Greasewood, sagebrush, and rabbitbrush all showed little change in the $T_c - T_a$ values, which were generally negative, suggesting that the plants were able to maintain lower canopy temperatures through evaporative cooling associated with transpiration loss despite having declining leaf xylem water potential (ψ_L) values (Figure 15). Shadscale showed distinct signs of

physiological stress with many Tc-Ta values being positive during the growing period indicating that shadscale was not transpiring at a high enough rate to maintain lower canopy temperatures.

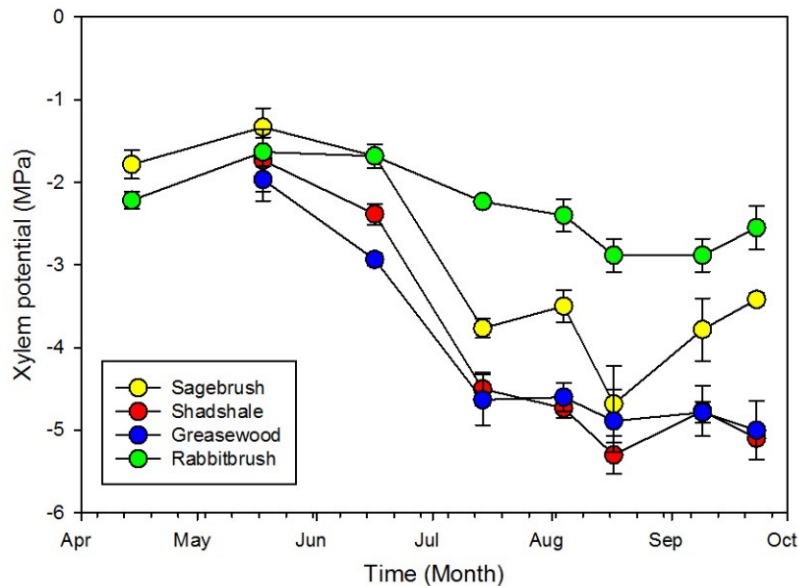


Figure 15: Leaf xylem water potential (ψ_L) for all four species for the duration of the growing period at SV6 site.

Evapotranspiration Relationships

Backward stepwise regression was used to evaluate the relationship between ET and precipitation (rain), potential evapotranspiration (ET_o) and species specific change in soil moisture in storage (Δ storage) (Table 5). A decrease in storage led to increased ET estimates for both sagebrush and rabbitbrush with rain contributing in a positive way to higher ET values. However, in shadscale, storage change was correlated with positive storage change, not depletion, and with higher ET during lower ET_o periods. No ET correlations were observed with greasewood which was likely a reflection of a groundwater extraction component complicating the upper storage change correlation.

Table 5: Statistical analysis of ET vs. species specific storage change (Δ storage), rain, and ET_o for the SV6 site.

Species	Statistical Analysis	R^2	P	Removed
Sagebrush	$ET = 1.035 - 0.948 \Delta \text{ storage} + 1.405 \text{ rain}$	0.992	<0.005	ET_o
Shadscale	$ET = 10.361 + 1.072 \Delta \text{ storage} - 0.252 ET_o$	0.967	<0.05	Rain
Rabbitbrush	$ET = 1.763 - 0.622 \Delta \text{ storage} + 1.110 \text{ rain}$	0.976	<0.05	ET_o
Greasewood	ET=Failed	-	-	All

Leaf area index (LAI) and chlorophyll index were assessed for all four species throughout the growing period (Figure 16). LAI measurements were taken monthly while chlorophyll measurements were taken bi-monthly. No LAI measurements were collected in June 2010 due to unavailability of the instrument. All species showed similar trends between LAI and the chlorophyll index. Sagebrush showed little change in LAI with values beginning at approximately $3 \text{ m}^2/\text{m}^2$, gradually increasing to $4 \text{ m}^2/\text{m}^2$ into July before declining back to approximately $3 \text{ m}^2/\text{m}^2$ throughout the remainder of the growing period. The chlorophyll index showed a similar trend, but showed a more significant increase in values from approximately 100 to 140 in mid-May before a steep declining trend to approximately 70 in late September.

The LAI data suggest that sagebrush responded early in the season by developing a larger canopy, but showed gradual reduction in canopy cover throughout the growing season suggesting sagebrush was under some physiological stress during the warmer summer months. Shadscale showed similar trends to sagebrush with LAI values climbing to a peak value of approximately $6 \text{ m}^2/\text{m}^2$ in July before beginning a downward trend through September where LAI values declined to approximately $3 \text{ m}^2/\text{m}^2$. Shadscale chlorophyll index also showed an early increase in values with a consistent decline through the growing period after June from

approximately 110 in early June to 70 in late September. Shadscale responded in a similar fashion as sagebrush, with early seasonal growth followed by a steady decline in canopy through the end of the growing season, as shadscale also showed signs of stress during the warmer summer months. Greasewood and rabbitbrush both showed similar growth trends with LAI and chlorophyll index values both rising early in the growing season but rabbitbrush appeared to have a much more favorable physiological status. Greasewood exhibited increasing LAI values from May into late June (approximately 2 to 5 m²/m²) with chlorophyll index values increasing between May and mid- July (approximately 90 – 130) before declining through September as the plants approached winter dormancy suggesting that greasewood showed some signs of plant stress with the reduction of canopy in the late summer. Rabbitbrush LAI showed the highest increasing values from May into August (approximately 4 to 6 m²/m²) and highest chlorophyll index values that increased between May and July (approximately 100 to 160) before both LAI and the chlorophyll index began to decline in late July and August through the end of the growing season.

These data suggest that rabbitbrush maintained a more favorable canopy throughout the summer months than the other three species before rabbitbrush showed signs of stress in late summer. LAI incorporates both living and dead biomass since readings are measured above and below the canopy, accounting for all plant material. LAI measurements may have been artificially inflated for some data collected because it incorporated twigs, branches, and even dead biomass; therefore, chlorophyll readings were likely more representative of plant health and physiological status.

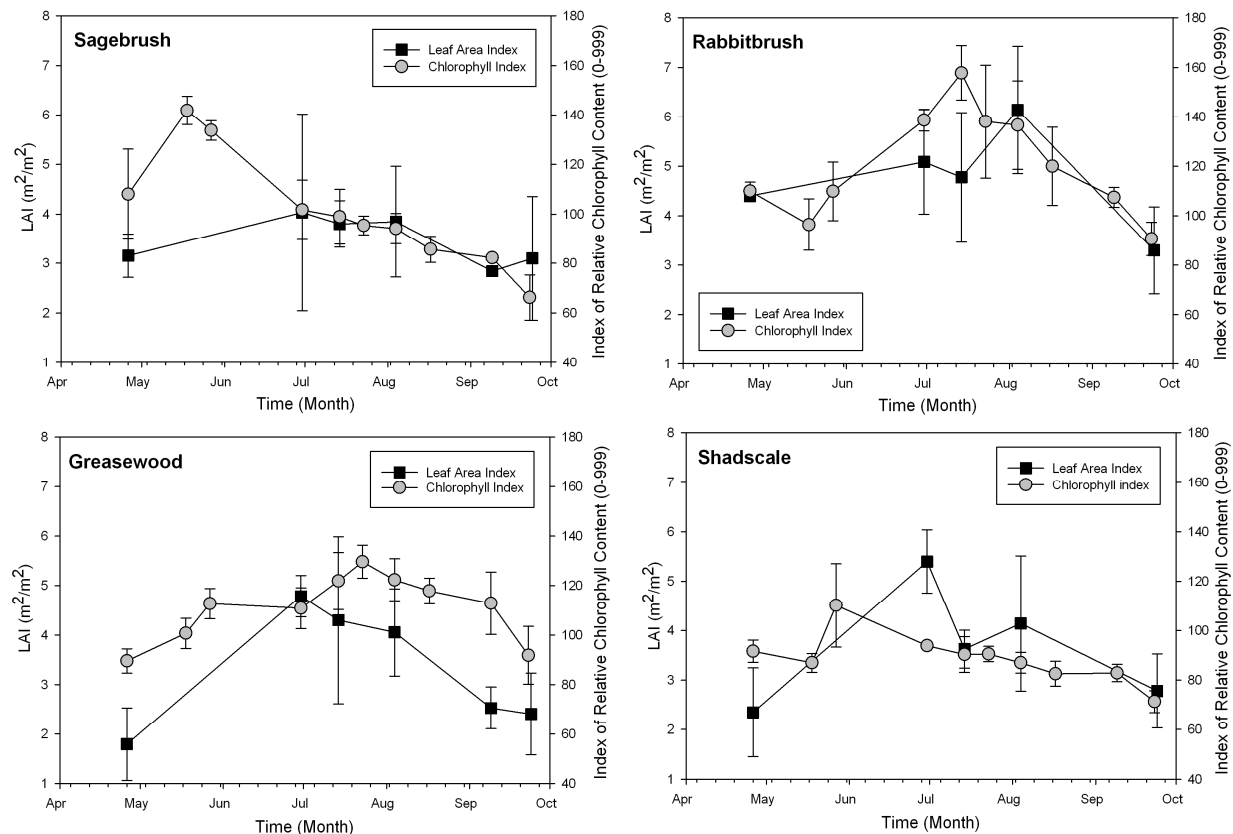


Figure 16: Leaf area index (LAI) and index of relative chlorophyll (chlorophyll index) was collected for all four species throughout the growing period.

Ground Based NDVI

To gain a better understanding of the phenological changes associated with each species, average midday (1100 to 1400) ground based NDVI values were obtained during the monitoring period. Due to installation delays and compatibility issues, a full time series response was only available for greasewood. Data collection for all other species began on May 27, 2010 and concluded on September 23, 2010. Also, between July 7 and July 23, 2010 there was a power outage at the site resulting in a gap in mean NDVI midday values. NDVI data were collected for shadscale and rabbitbrush over a total period of 103 days with measurements beginning on May 26, 2010 and concluding on September 22, 2010. The sagebrush sensor malfunctioned repeatedly

and although it collected data from March 1, 2010 to November 3, 2010, minimal data points were within range due to potential reflectance disturbance from a sap flow system installed on the plant (Figure 17). As such, the data during the latter part of the monitoring period are questionable.



Figure 17: Sagebrush NDVI setup at SV6 site. Note the installation of sap velocity sensors at the base of the plant that may have led to impacts on the NDVI data.

Figure 18 represents the phenological changes over the course of the growing period for greasewood at SV6. The dormancy phase represented complete defoliation during the winter months. The active growth phase depicts a rapid increase in NDVI from 0.110 on April 19 to 0.571 on June 10 as the plant actively produced new leaves associated with warmer temperatures in late spring and early summer (Table 2).

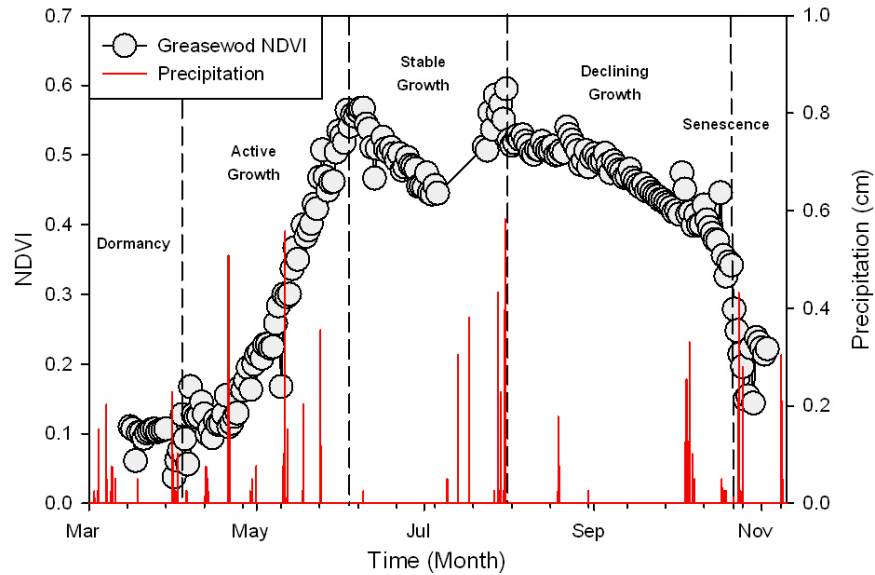


Figure 18: Time series of average midday (1100–1400) NDVI values for a single greasewood plant at the SV6 site. NDVI data for the greasewood plant were acquired from March 16, 2010 to November 3, 2010.

During the stable growth phase, there was a slight decline in NDVI showing the first signs of summer water stress with NDVI values reducing from 0.571 to 0.440 between June 10 and July 1. There was a data gap due to sensor failure between July 5 and July 21, but data acquired from July 21 to July 31 revealed an increasing trend in NDVI from 0.509 to 0.592 in response to mid-summer precipitation events, that totaled 1.88 cm of precipitation between July 26 and July 30. During the late summer months, greasewood showed signs of physiological stress with a sharp decline in canopy density and NDVI values (0.526 – 0.354). There was a decline in NDVI values from 0.354 on October 18 to 0.149 on October 29 when greasewood began leaf senescence in preparation for winter dormancy.

Bare soil (loam texture in the upper 20 cm) at the SV6 site produced low NDVI values ranging between 0.095 and 0.135 with spikes in data observed during precipitation events (Figure 19).

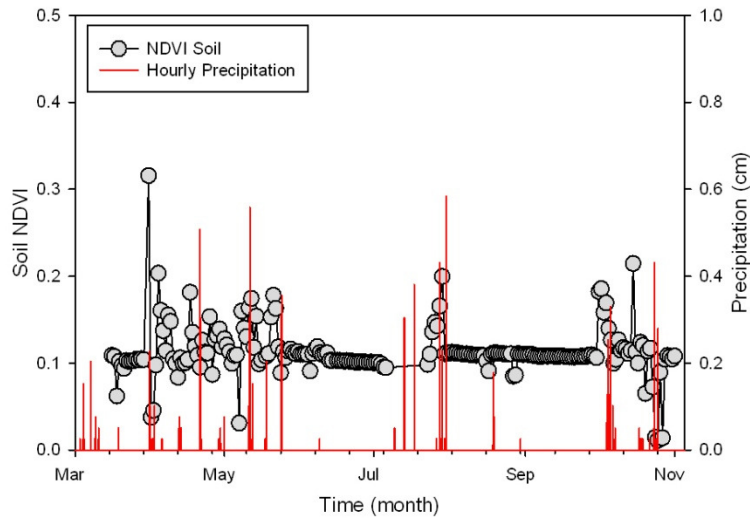


Figure 19: Time series of average midday (1100–1400) NDVI values for bare soil at the SV6 site. NDVI data were acquired from March 16, 2010 to November 3, 2010 with revealing the NDVI response for bare soil to precipitation events.

Rabbitbrush and shadscale NDVI data remained fairly stable during the monitoring period. However, both species appeared to respond to rainfall during the late spring with rabbitbrush NDVI increasing from 0.303 to 0.462 between May 28 and June 11 then declining again from June 11 to July 6 to 0.345 during an extended period of low precipitation and warmer temperatures (June temperatures averaging 25.6°C) (Figure 20). Shadscale revealed a similar trend to the late May precipitation events increasing NDVI values from 0.401 on May 28 to 0.582 on June 28, declining slightly later than rabbitbrush to 0.560 by July 6. Both species revealed an increase in NDVI in late July following three precipitation events (0.367 on July 23, 0.412 on August 7, and 0.418 on August 18) suggesting precipitation was being utilized as a source of water. As precipitation events ceased in the fall, both species began to show declines in NDVI values with shadscale reducing NDVI from 0.604 on August 30 to 0.534 by September 22 and rabbitbrush NDVI dropping from 0.418 on August 18 to 0.281 on September 23.

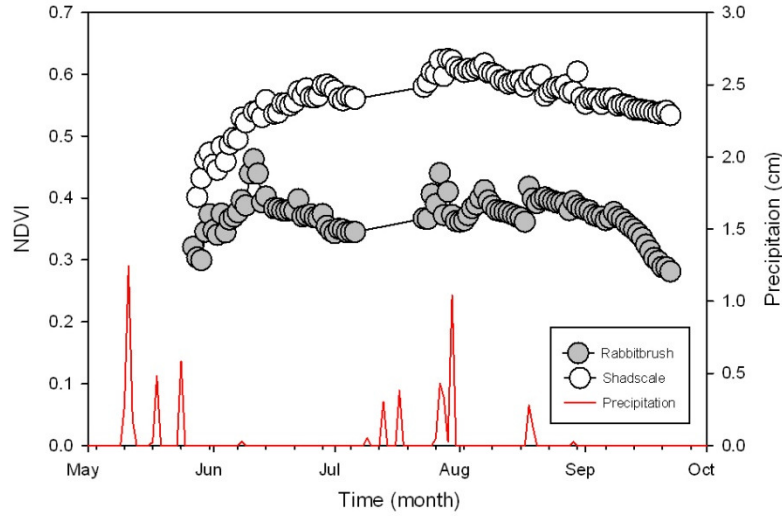


Figure 20: Series of average midday (1100–1400) NDVI values for rabbitbrush and shadscale at the SV6 site along with precipitation events. NDVI data were acquired for rabbitbrush and shadscale between May 27, 2010 and September 23, 2010.

Isotopic Analysis for Determination of Plant Water Extraction

Within the upper 100 cm, soil water content and plant water uptake was influenced by precipitation and redistribution with a linear decrease in $\delta^{18}\text{O}$ observed ($R^2=0.799$) from soil water collected with depth associated with all species. Values in the near surface region were similar to values for precipitation, whereas $\delta^{18}\text{O}$ in deeper depths declined to values as low as -23‰ at the 100 cm depth (Figure 21).

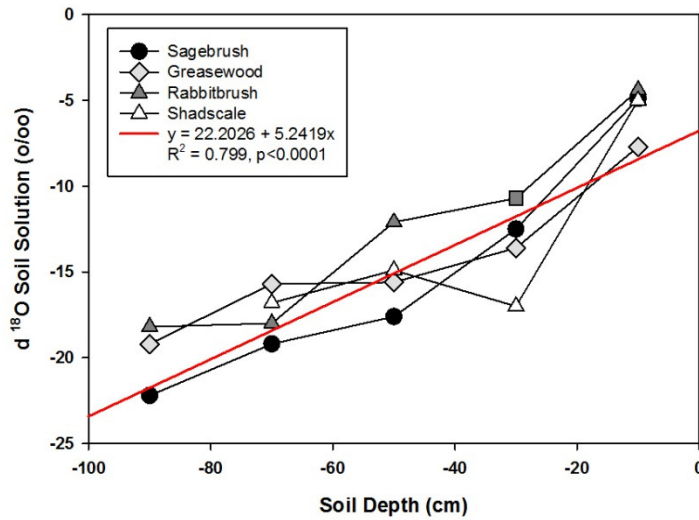


Figure 21: A decrease in $\delta^{18}\text{O}$ was observed with depth associated with all four species combined at the SV6 site.

Groundwater samples had values of $\delta^{18}\text{O}$ ranging from -16.6 to -16.8 ‰ whereas precipitation samples had $\delta^{18}\text{O}$ values between -6.5 to -15.1 ‰. Analysis of soil water revealed a consistent decrease in $\delta^{18}\text{O}$ with depth through 200 cm where the $\delta^{18}\text{O}$ value reached a minimum of -25 ‰. Beyond the 200 cm depth, $\delta^{18}\text{O}$ values started to become less negative (to 340 cm) as the deeper soils approached the values of the groundwater (Figure 22).

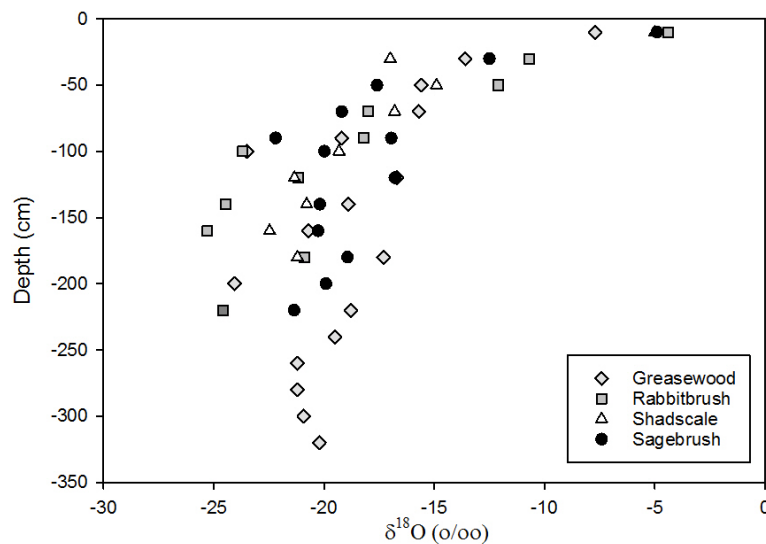


Figure 22: $\delta^{18}\text{O}$ soil water values from 0 cm to 340 cm revealed a decrease through 200 cm where values began to increase at depths closer to the groundwater.

Uptake of $\delta^{18}\text{O}$ by the plants was assessed by sampling woody twigs from the shrub canopies on a monthly basis during the study. Results reported in Figure 23 reveals that $\delta^{18}\text{O}$ levels in the tissue became more negative with time. Only in the case of greasewood did the $\delta^{18}\text{O}$ values in the tissue become more negative than that found in the groundwater. During May, values of $\delta^{18}\text{O}$ in the tissue of all four species were at levels similar to precipitation. However, in both greasewood and rabbitbrush, $\delta^{18}\text{O}$ became more negative by May, whereas in shadscale and sagebrush, $\delta^{18}\text{O}$ levels remained more positive and closer to values found in precipitation.

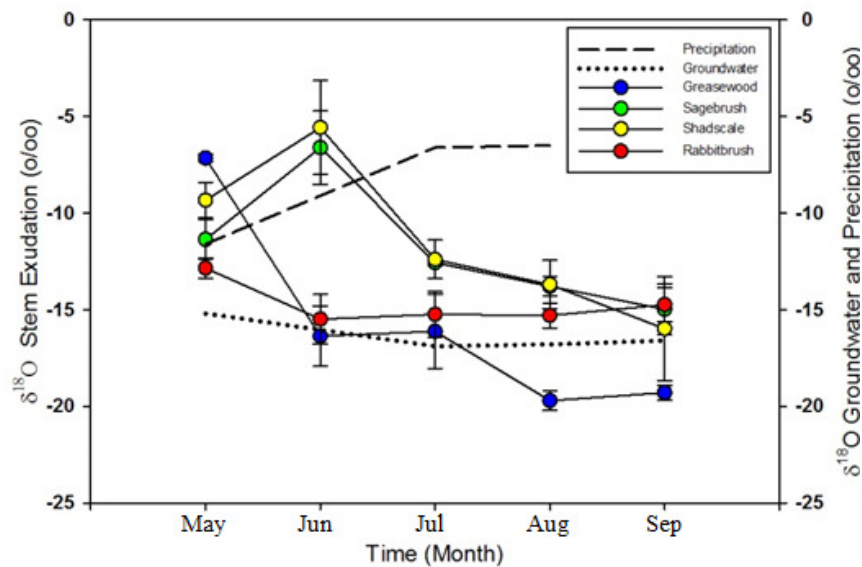


Figure 23: Greasewood $\delta^{18}\text{O}$ values showed a trend toward accessing deeper water with the onset of summer stress while the other three species $\delta^{18}\text{O}$ remained more positive and closer to values found in precipitation.

By plotting a combination of $\delta^{18}\text{O}$ in soil moisture with depth, $\delta^{18}\text{O}$ in groundwater, $\delta^{18}\text{O}$ in precipitation, and $\delta^{18}\text{O}$ from stem exudates, distinct species specific trends were clearly observed between the four species (Figure 24).

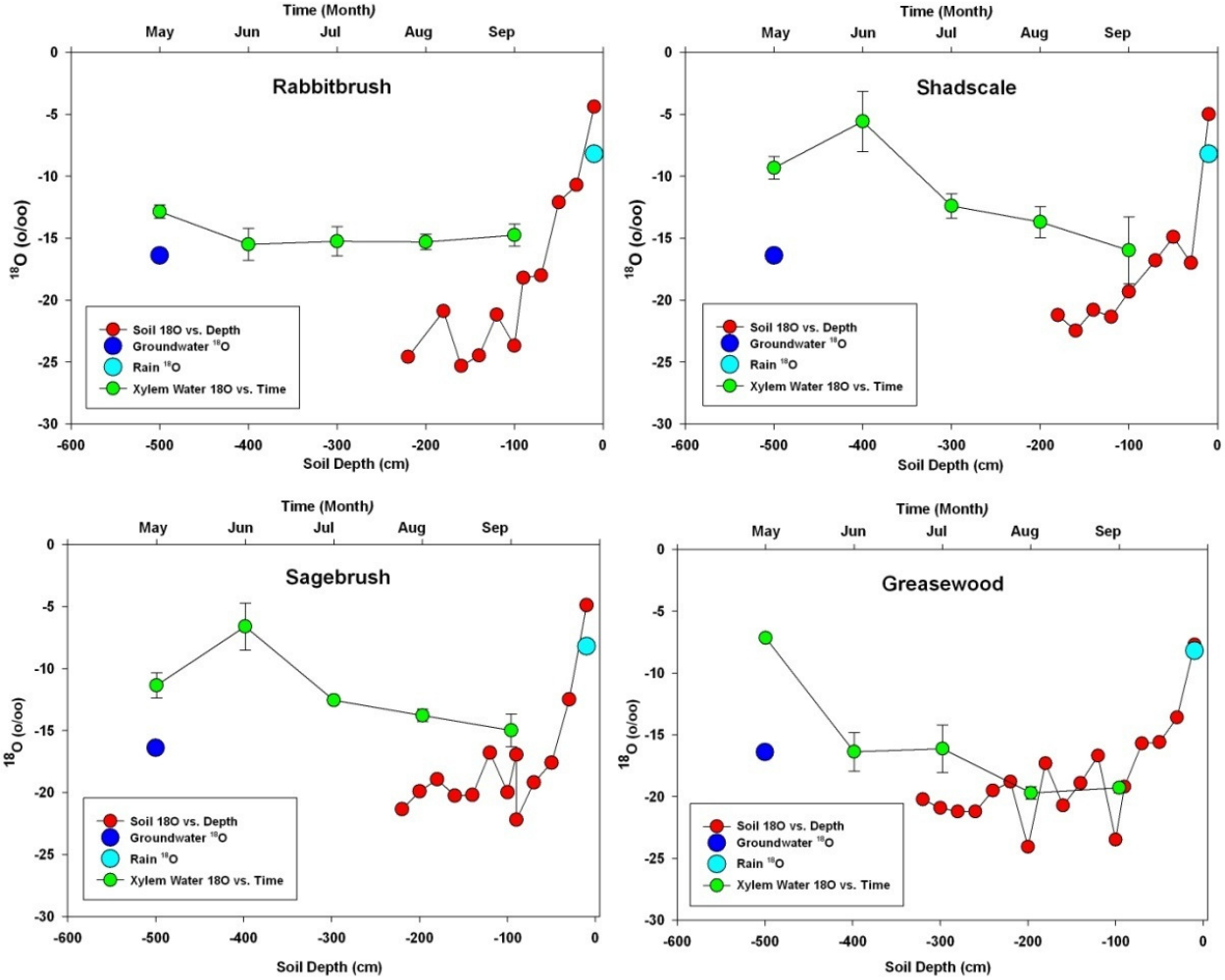


Figure 24: A combination of $\delta^{18}\text{O}$ soil moisture by depth, $\delta^{18}\text{O}$ of groundwater, $\delta^{18}\text{O}$ of precipitation, and leaf xylem $\delta^{18}\text{O}$ from stem exudates for all species.

Shadscale and rabbitbrush showed similar trends with both species showing an increase in $\delta^{18}\text{O}$ between May and June. Sagebrush $\delta^{18}\text{O}$ values shifted from approximately -11 to -7 ‰ and shadscale from -9 to -6 ‰, between May and June. Thereafter, both species showed a slight downward trend through September with stem exudate $\delta^{18}\text{O}$ values for sagebrush decreasing from -13 to -15 ‰ and shadscale stem exudate $\delta^{18}\text{O}$ decreasing from -12 to -16 ‰. When comparing the soil $\delta^{18}\text{O}$ values of shadscale and sagebrush stem exudates, $\delta^{18}\text{O}$ values were consistent with values in the soil water observed in the upper 50 cm (approximately -5 to -17 ‰)

and similar to values of $\delta^{18}\text{O}$ observed in precipitation (approximately -8 ‰), suggesting these two species were accessing water in storage recharged by precipitation, especially within the upper 50 cm, but as the summer environmental demand increased, both species began utilizing soil moisture deeper within the soil profile but probably still within the upper 100 cm. The greasewood initially showed stem exudate $\delta^{18}\text{O}$ values in May of approximately -7 ‰, similar to that observed in precipitation (approximately -8 ‰), but immediately decreased $\delta^{18}\text{O}$ values to approximately -16 ‰, values similar to those seen in groundwater into July and then showed another gradual decrease in $\delta^{18}\text{O}$ values to -19 ‰ through September. These values suggest greasewood was accessing water deeper within the profile than the other species, with late season values of -19 ‰ suggesting that greasewood was likely accessing a combination of groundwater and water within the vadose zone. Also, values for greasewood $\delta^{18}\text{O}$ approached groundwater as early as June suggesting greasewood may have been accessing groundwater early in the growing period. Devitt et al. (2015) observed deep vadose zone diurnal soil water oscillations at 800 and 900 cm as early as May indicating greasewood was accessing groundwater recharged sediments earlier in the growing season.

Rabbitbrush showed values that were relatively stable with little change in $\delta^{18}\text{O}$ from May to October. Values ranged between -13 and -15 ‰ which were lower than precipitation but higher than groundwater with little variation. Soil $\delta^{18}\text{O}$ values between 50 – 70 cm of -12 to -18 ‰ suggest that rabbitbrush may have been accessing a reliable water source deeper in the upper vadose zone not being accessed by the other three species, likely within the 50 – 80 cm depth where $\delta^{18}\text{O}$ were similar to those observed in stem exudate for this species and was most likely limited to the upper 100 cm by the high salinity below this region.

CHAPTER 5 DISCUSSION

Groundwater levels

Groundwater levels at the SV6 site revealed recharge to the groundwater system through May 2010 after which the water table began to show a distinct decline through the remaining growing season. However, in October water levels began to rise again once the phreatophytic plants entered into dormancy and irrigation withdrawals in the valley diminished. The groundwater extraction period was consistent with isotopic analysis and physiological plant response measured at this site. Steinwand et al. (2006) and Devitt and Bird (2015) suggested that the presence and disappearance of diurnal water table fluctuations can be indicators of phreatophyte coupling/decoupling to the groundwater system. Steinwand et al. (2006) found varied levels of dependence of phreatophytic vegetation on groundwater. Diurnal water table fluctuations due to phreatophytic plant water uptake from the groundwater were observed at the SV6 site prior to the well having been re-screened in 2009. Once the well at SV6 was rescreened, the diurnal water table fluctuations disappeared suggesting that there may have been an artificial dampening of diurnal signals due to problems with the well screen. Elmore et al. (2006) documented the effects of groundwater pumping on large natural basins for the purpose of providing urban cities with a more sustainable water source. Such detrimental effects on basins could occur in Spring Valley and central Nevada where extended drought combined with groundwater pumping could lead to shifts in ecosystem function and possible decoupling of phreatophytic vegetation with groundwater resources. Therefore, further research is needed to determine whether phreatophyte induced diurnal water table fluctuations can be observed again at this site.

Water Balance and Eddy Covariance

The eddy covariance ET (ET_{EC}) estimate at the site was 22.63 cm while precipitation was measured at 8.92 cm giving an ET_{EC} - precipitation difference of 13.61 cm, with the imbalance being partitioned to groundwater extraction. This value however, does not account for utilization of soil moisture in storage. Water balance estimates of ET for the canopy and bare soil accounted for 16.09 cm. When the canopy and bare soil ET was subtracted from the ET_{EC} value of 22.63 cm 6.54 cm remained, suggesting that the remaining ET was likely attributed to groundwater (ET_g) extraction. To close the balance, using an ET_g value of 6.54 cm and subtracting this value from the ET_{EC} - precipitation value of 13.61 cm resulted in 7.07 cm attributed to soil water in storage. Devitt and Bird (2015) suggested that the method of using ET_{EC} - precipitation as a means to estimate ET_g has shortcomings since it does not account for storage changes within deep unsaturated zones. The finding in this study support Devitt and Bird (2015) as it is believed the groundwater values using ET_{EC} - precipitation were inflated when compared to species weighted water balance groundwater extraction estimates. This research concurs with Devitt and Bird (2015) that more groundwater ET_g information is needed to predict vegetative response to groundwater pumping.

Soil Moisture

Within the upper 50 cm region, soil moisture data revealed that sagebrush, greasewood, and shadscale showed similar soil moisture depletion. Also, similar relative storage trends were observed with time for these three species with greasewood and sagebrush showing nearly identical change in relative storage over the course of the growing season. Soil moisture data revealed that rabbitbrush was accessing soil moisture between the 50-80 cm range where no other species appeared to be accessing water. Redistribution of soil moisture was observed

within the 50-80 cm zone but storage values measured in this depth range beneath the rabbitbrush showed distinct reductions when compared to the other three species at the site. Rabbitbrush also showed a faster and higher depletion in relative storage than all three species suggesting that rabbitbrush was utilizing more water in storage than the other species in the upper 100 cm.

Salinity and Chloride Data

The data collected from the SV6 site suggested that greasewood was the only species at the SV6 site accessing groundwater due to the high salinity levels beyond the 100 cm region. Greasewood is a known halophyte capable of osmoregulation and is considered a salt tolerant species with the ability to penetrate high salt regions to access deeper groundwater (Conrad, 2008; Donovan et al., 1997; Devitt and Bird, 2015). Tissue ion analysis from a similar study in this region (Conrad, 2008) indicated no elevated levels of Cl or Na in the leaf tissue of rabbitbrush or sagebrush compared to greasewood. The salinity and chloride data revealed a steady state profile over the upper soil region with a highly linear ECe with depth relationship ($R^2 = 0.78$, $p < 0.001$) to 140 cm and highly linear chloride concentration with depth relationship ($R^2 = 0.60$, $p < 0.001$) to 120 cm suggesting this steady state pattern of water depletion has been maintained for a significant period of time. A 20-fold increase was observed in the soil salinity when the uppermost region was compared to the region below 100 cm, suggesting a long-term drainage component of less than 5%. Scanlon and Levitt (2005) suggested that chloride buildup as observed at this site requires greater than 10,000 years to form. Our data indicated a disconnect between surface hydrology and groundwater suggesting little if any recharge is occurring at this site.

Rabbitbrush is considered a Na-excluding glycophyte (preferring soils with low salinity) (Dodd and Donovan, 1999) with certain rabbitbrush sub-species of *Chrysothamnus nauseosus* (spp. *Consimilis*) being described as marginally salt tolerant (Roundy et al., 1981). It has also been noted that rabbitbrush can act as a phreatophyte (Groeneveld, 1990). However, with ECe levels exceeding 30 dSm^{-1} ($> 50 \text{ dSm}^{-1}$ in soil solution) between 120 – 180 cm at the SV6 site, it is unlikely that rabbitbrush would be able to extend roots beyond 120 cm due to this high salinity. There was no evaluation of root distribution during this study. It may be that rabbitbrush has a more extensive shallow root system moving further out from the base of the plant accessing a greater water reservoir, especially in the 50 – 80 cm region where soil water content was significantly lower throughout the study period compared to the other species. More research is needed to determine the root characteristics and specific water utilization for rabbitbrush.

Physiological Plant Responses

Rabbitbrush maintained a more favorable plant water status with maximum ψ_L value of -2.9 MPa observed in August whereas the other three species at the SV6 site showed ψ_L beyond -4.0 MPa during the summer months. Greasewood and rabbitbrush both showed similar growth trends with LAI and chlorophyll index values both rising early in the growing season but rabbitbrush maintained a more positive leaf xylem water potential throughout the entire experimental period. Greasewood, sagebrush, and rabbitbrush all showed little change in the Tc-Ta values while shadscale showed several positive values for Tc-Ta. Shadscale was unable to always maintain canopy temperatures below ambient temperatures which indicated signs of physiologic stress for this species. Greasewood and sagebrush were able to maintain lower canopy temperatures despite having leaf xylem water potential values that became more negative.

NDVI

Ground based NDVI was successfully utilized in this study to track the complete phenology for greasewood while also revealing different trends for both rabbitbrush and shadscale, confirming previous work by Baghzouz et al. (2010) that ground based NDVI is a powerful tool in assessing the temporal phenology of desert shrub communities.

Bare soil NDVI revealed spikes in data observed during precipitation events. This change in NDVI is related to a significant color change and shift in reflectance. However it can also be partially due to biogenic soil crusts. When biogenic soil crusts are wet, their NDVI values can reach 0.30 due to their shift in photosynthetic reflectance at 670 nm (Karnieli et al., 2014). According to Karnieli et al. (2014), biogenic soil crusts respond quickly to a wetting event by transitioning into a photosynthetically active state until they dry out and return to a dormant state until the next wetting event. Biogenic soil crust activity at SV6 may have contributed to inflated bare soil NDVI values after precipitation events but more detailed information is needed to determine the biogenic soil crust NDVI contribution.

Isotopic analysis

Isotopic analysis of soil water, groundwater, and plant xylem tissue revealed species specific trends in $\delta^{18}\text{O}$ values and confirmed findings of Chimner and Cooper (2004) that stable isotopes can be used to identify the water source for primary shrubs. Results from this study suggest that the greasewood, being a facultative phreatophyte (Meinzer, 1927), was accessing both water within the 0-40 cm region and groundwater as early as May. Isotopic stem exudate analysis revealed $\delta^{18}\text{O}$ values similar to those measured for precipitation early in the growing season, similar to the values seen for sagebrush and shadscale. However, greasewood appeared to be the only species that showed isotopic $\delta^{18}\text{O}$ values that became more negative than groundwater $\delta^{18}\text{O}$

values with the onset of summer stress. Isotopic $\delta^{18}\text{O}$ values suggested that the greasewood was accessing a combination of groundwater and water within the vadose zone which was consistent with the findings of Devitt and Bird (2015) that greasewood can begin accessing groundwater early in the growing period and continue to access a combination of groundwater and water from the vadose zone throughout the growing season.

Analysis of $\delta^{18}\text{O}$ stem exudate values for rabbitbrush in conjunction with $\delta^{18}\text{O}$ soil moisture extracts are consistent with the idea that rabbitbrush was accessing water from the 50-80 cm zone, allowing it to maintain a more favorable water status compared to the other species which were primarily utilizing soil water within the upper 50 cm. However, rabbitbrush had a very low contribution to the overall canopy cover (1.7 %). As such, more research is needed to determine the extent of the rooting system and water extraction characteristics for this species.

CHAPTER 6 CONCLUSIONS

In this study, the objective was to utilize field techniques such as eddy covariance, hydrologic balances, isotopic analysis of soil plant and water samples and physiological parameters to assess the linkage between water source and water use. It was hypothesized that a combination of eddy covariance data, soil moisture, and plant specific measurements could be used to estimate species and community level ET and also the degree to which the species rely on water within the vadose zone versus the groundwater. This study was successful in using the aforementioned field techniques to estimate community level ET values. It was also hypothesized that isotopic analyses of stem exudation, soil moisture, and groundwater could be used to assess the dependence for each species on a given water source. Isotopic analysis was successful in determining plant water source at this field site and revealed that greasewood was likely accessing groundwater earlier in the season than previously recorded as suggested by Devitt and Bird (2015).

As previously mentioned, climate models predict the western United States will continue on a trend towards a warmer and dryer climate with temperature increases projected at 2 to 4 °C by 2050 (Barnett and Pierce, 2008; Christensen et al., 2004). Additional stress of groundwater pumping to the fragile and dynamic ecosystem in Spring Valley could exacerbate the decoupling of phreatophytes from groundwater resources.

Water balance data from the SV6 site revealed that groundwater is accounting for approximately 29 % of the overall ET. Greasewood was the only known phreatophyte at this site and accounted for 17.4 % of the living cover. With groundwater accounting for such a high percentage of the overall ET contribution at this site, a decrease in groundwater levels due to climate change combined with groundwater pumping could lead to decoupling of this

phreatophytic species from groundwater resources. Greasewood is a facultative phreatophyte; therefore, removing groundwater as an available water source for this species could potentially lead to this plant becoming completely reliant on precipitation and soil water in storage. This decoupling could potentially add stress to an already fragile environment.

Data from this study revealed that the dominant species sagebrush, which accounts for 56.6 % of the living canopy cover at the SV6 site, showed signs of physiological stress during summer months due to depletion of soil moisture in storage. Data revealed ψ_L values beyond -4.0 MPa and soil volumetric water content values in the upper 50 cm showed a decline from approximately $\theta = 0.20$ in April to $\theta = 0.04$ by the end of the growing season. Data also revealed that greasewood showed similar depletion of soil water content within the upper 50 cm, reducing its volumetric water contents from approximately $\theta = 0.21$ in April to $\theta = 0.12$ in September suggesting that greasewood was utilizing and extracting soil moisture from the same region as sagebrush. If greasewood could no longer utilize groundwater as a reliable source of water, it would have to shift to a primarily precipitation driven survival, depleting soil water resources from surrounding vegetation. This could have detrimental effects to species such as sagebrush that rely solely on soil moisture in storage and precipitation for survival and for sensitive species that rely on these shrubs for food and shelter.

Desertification is defined as the loss of perennial vegetation in arid and semi-arid regions and is considered one of the ecological threats facing the world today (Kassas, 1995). Dieback and/or ecological shifts in the sagebrush population could have devastating effects on animal populations that are reliant on sagebrush for habitat and grazing. If dieback became severe, this potentially could lead to desertification of Spring Valley, similar to that observed in Owens Valley CA (Elmore et al., 2006). Recent evaluation of Great Basin habitat threats identified 207

species of conservation concern including 133 plants, 11 reptiles and amphibians, and 63 birds and mammals including species of particular concern such as sage grouse (*Centrocercus* spp) and pygmy rabbits (*Brachylagus idahoensis*) among others (Knick et al. 2003; Rowland et al., 2005).

Vegetative reductions of sagebrush and/or greasewood stands in Spring Valley could also potentially lead to increased top soil erosion leading to the inability of perennial plants to recolonize seedlings and establish new growth further exacerbating soil erosion and stability issues (Scheffer et al., 2001). Increased plant stress and/or dieback of sagebrush and/or greasewood could increase wildfire dangers with excess dead or dry material being available as fuel for fire. Climate change and ecological shifts can influence wildfire activity. Jolly et al. (2015) has determined that fire weather seasons have lengthened for 25.3 % of the Earth's vegetated surface and is resulting in an 18.7 % increase in global mean fire weather season length. If groundwater pumping and climate change leads to species stress and dieback in Spring Valley, wildfire activity could increase within this region.

A combination of climate change and reduction in groundwater could have significant consequences on all the aforementioned parameters and increase the likelihood of fires, erosion, loss of vegetation cover, and shifts in ecosystem dynamics. The information provided in this research study should be useful in assisting future management of groundwater resources and minimizing vegetation impacts within Spring Valley. If the goal of water managers is to maintain existing vegetation while also utilizing groundwater resources for anthropogenic use, further research is necessary to determine the maintenance of groundwater depths that are critical to the survival of phreatophytic species within Spring Valley prior to ecological stress and/or dieback.

In conclusion, further research and long term monitoring of phreatophytes is essential if pumping and groundwater deportation from central Nevada is going to occur.

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