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Investigation of plant water use in the Great Basin, NV

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INVESTIGATION OF PLANT WATER USE IN THE GREAT BASIN, NV

by

Benjamin Conrad

Bachelor of Sciences
Truman State University
2003

A dissertation submitted in partial fulfillment
of the requirements for the

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School of Life Sciences
College of Sciences

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ABSTRACT

Investigation of Plant Water Use in the Great Basin, NV

by

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Global climate change in addition to a growing population can have a strong impact on our natural resources. In particular, cities in the semi-arid and arid southwestern US are currently faced with the challenge of providing sustainable fresh water to a growing population. In Las Vegas, dwindling water levels in Lake Mead have forced water managers to seek water resources from Spring Valley and Snake Valley, NV, which are located 402 km north of the city. The goals of this research were to investigate the water use of shrubs located in these valleys by using a large aperture scintillometer (LAS) to scale up energy balance components (needed to close a water balance) from the canopy level and to determine the potential impacts of altering the water source available to these native vegetation communities. Due to proposed groundwater pumping to Las Vegas, we focused mainly on the facultative phreatophytic shrub *Sarcobatus vermiculatus* (greasewood). Phreatophytic shrubs have a large tap root that accesses ground water within a phreatophytic zone directly above the water table, and they are characterized by being either obligate (living almost entirely off of

ground water) or facultative (the ability to survive off of either groundwater or vadose zone soil moisture).

This study demonstrates the validity of using a LAS to measure energy balance components over heterogeneous landscapes in a semi-arid environment, as well as the potential impacts that a rapidly falling water table can have on native vegetation. This information could be combined to help mitigate negative impacts from long term water acquisition from these valleys, and help to combat against drastic changes to the natural ecology existing in these valleys.

In Chapter 2 we demonstrate the ability of the LAS to be used in a semi-arid environment within a heterogeneous landscape to estimate energy balance components by comparing LAS sensible heat values (H_{LAS}) to those obtained from an eddy covariance station (H_{EC}). Correlation coefficients between the two techniques for four measurement periods over the growing season of 2005 were as follows: 0.98 on 4-14-05; 0.85 on 6-1-05; 0.85 on 7-19-05, and 0.89 on 9-5-05, with all $p < 0.001$. These results suggest an alternative technique for measuring sensible heat flux over much larger footprints than possible by the EC station alone, which are needed to close a water balance. Future research is needed to determine the effectiveness of the LAS for determining basin wide evapotranspiration values when combined with satellite data.

The plant water use of *S. vermiculatus* during the growing season of 2007 is investigated in Chapter 3. Here we use a sap flow system to estimate transpiration across three treatments: severed tap (ST), infiltration prevention (IP) and True Control (TC). Our data suggest that severing the tap root of this phreatophytic shrub has a greater effect on sap flow than preventing rainwater infiltration. Furthermore, we demonstrate the

ability of this species to respond to episodic rainfall events by increasing their sap flow in response to increased soil moisture. Results from this study may provide valuable information on how this species could respond to a rapidly declining water table in Spring Valley and Snake Valley, NV.

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CHAPTER 1

GENERAL INTRODUCTION

Native plant communities are intricately linked to watershed hydrologic processes. As such, any deviation in water availability, whether by natural or anthropogenic causes, may have a negative impact on the overall health and productivity of the plant community. Alterations in available water may occur by stream flow diversions (Busch et al., 1992; Mahoney and Rood, 1992; Elmore et al., 2003) containment of runoff (Horton et al., 2001) and/or increased ground water pumping (Scott et al., 2000; Zencich et al., 2002; Naumburg et al., 2005). These alterations may lead to plants becoming decoupled from ground water and dependent completely on soil moisture located in the vadose zone (Busch et al., 1992). When water tables drop below 2 m depth, plants that are most affected by alterations in the water table are shallow rooted phreatophytes. Phreatophytes are a class of plants that can develop a root system capable of tapping groundwater sources to meet plant water requirements. Within this general classification are obligate phreatophytes such as *Populus* (cottonwoods) and *Salix* (willows), which are totally dependent on groundwater and facultative phreatophytes such as *Tamarix* (saltcedar), which are capable of shifting water uptake from ground water

to vadose zone soil water to groundwater, based on availability and demand (Busch *et al.*, 1992). In either case, all plants, including phreatophytes, have physiological limits on the depth to which they can develop root systems and maintain root contact with falling water tables (Lite and Stromberg, 2005). Once the rooting limit has been exceeded and water resources (soil moisture, ground water) are no longer readily available, plants will begin to demonstrate stress at both the leaf and community levels.

Physiologically, plants may respond to water stress by decreasing shoot water potential and stomatal conductance, while at the morphological level, plants may exhibit leaf xeromorphy and a reallocation of nutrients from above to below-ground production (Cooper *et al.*, 2003). Furthermore, extreme water stress can cause xylem cavitation resulting in embolisms (Kolb and Sperry, 1999), and premature leaf senescence, branch mortality, and ultimately plant death (Cooper *et al.* 2003). At the community level, a drastic change in water table levels may gradually alter vegetation (species compositions and percent cover). For example, it has been demonstrated that water table depth is a keystone factor in determining vegetative cover across varying ecotones (Groeneveld and Or, 1994). In these instances, invasive species, such as the facultative phreatophyte *Tamarix*, can out-compete native obligate phreatophytes such as *Populus* and *Salix* and other shallow rooted riparian species (Busch and Smith, 1995, Lite and Stromberg, 2005). This problem is exacerbated by natural and anthropogenic fires, which allow species such as *Tamarix*, with much faster growth rates, to replace native vegetation (Busch and Smith, 1993).

The sensitivity of native vegetation to falling water tables presents a difficult task for the management and restoration of floodplain ecosystems. Moreover, though a drop in

the water table potentially causes stress, rapid rises in the water table depth are also problematic, because the plant needs to constantly readjust its root system to new water table levels. Therefore, the influence of fluctuations in the water table is difficult to determine because frequency, timing, rate, duration, species specific traits, grazing and disease will all affect how severely root systems and water uptake are compromised (Naumburg, et al., 2005). Therefore, a good understanding of both physiological and community responses to changing water tables is needed as a starting point before water acquisition strategies are developed.

Causes of Water Table Drawdown

Water tables will fluctuate due to natural and anthropogenic causes. In the former case, water tables will fluctuate due to climatic (or seasonal) changes. These changes are greatest when winter and summer periods are contrasted in terms of precipitation and evapotranspiration, mainly because of changes in recharge rates. Under steady state conditions these periodic changes in recharge will result in yearly oscillations in the water table depth. Long-term climate change is also a potential cause of water table fluctuations (Breeuwer et al., 2008).

Other causes of water table fluctuations may be anthropogenic in nature, which could be embedded onto natural cycles, and lead to non-periodic behavior of groundwater resource availability for plants. These anthropogenic causes can lead to dramatic responses in plant communities in semi-arid and arid regions where water supply is limited. In particular ground water changes can affect desert riparian ecosystems where many native plant species are coupled to shallow ground water sources.

In the American Southwest, riparian ecosystems compose less than 3% of the landscape area, but they support a wide array of wildlife habitat, biodiversity, unique native vegetation and recreational opportunities (Horton and Clark, 2001). The recent growth of population centers in the southwest, US has placed stress on many riparian ecosystems as a greater percentage of available water resources have become committed. Stream diversion has become an important means of supplying both water and power to rapidly developing cities, but projects such as dams and diversions have been documented to contribute to the decline of many southwestern riparian forests (Horton and Clark, 2001). The dams and diversions can cause water table decline by altering the hydrology of the river, which can reduce sediment loads and increase erosive power, causing greater channel incision and water table decline (Horton and Clark, 2001). Furthermore, dams and diversions can change the timing of peak flows, which can greatly limit the regeneration of native vegetation, leaving open the opportunity for exotic species to propagate under drier conditions (Horton and Clark, 2001). The alteration in peak flow timing is an important factor when establishing riparian vegetation, which requires high flows in the spring that scour competing vegetation and deposit fresh alluvium, which in turn creates ideal germination sites (Horton and Clark, 2001). A gradual recession in flows is also required following germination to allow seedlings aerated soils while remaining in contact with the capillary fringe (Mahoney and Rood, 1991). Effects of stream flow diversion have been clearly demonstrated in the Southwest over the past 100 years, where many native species along riparian corridors have been replaced by exotics such as *Tamarix ramosissima*. *Tamarix* has greater seed dispersal capabilities and higher seed viability than native species such as *Populus* and *Salix* and is

relatively intolerant of flood disturbance and extended inundation which makes regulated rivers an ideal habitat for this invasive species (Shafroth et al., 2002). Outside of the riparian corridors, native species are also facing similar levels of water stress wherever ground water is being actively pumped to service irrigated agriculture or large population areas. It is in these locations that the survivability of a species is intricately linked to their degree of reliance on the water table.

Ground water pumping is one of the most direct means of supplying cities with their water supply, because surface water is typically appropriated by existing state, interstate, and international treaties (Cooper et al., 2003). However, the amount of ground water extraction taking place varies greatly and is highly dependent on the local hydrology, climatic conditions and the communities' water portfolio. In pre-development Las Vegas, large parts of the valley were under artesian pressure and direct ground water extraction was not necessary. This reliable water source supported thousands of hectares of salt grass and alkali sacaton along, with a 1619 hectare Mesquite bosque (Devitt et al., 2002). However, as Las Vegas grew and more ground water was pumped, water tables began to drop and native vegetation failed to maintain its growth and regeneration (Devitt et al., 2002).

In arid and semi-arid climates, where the groundwater supply is not sufficient, water sources can be long distances from the tap. For example, Los Angeles, which receives only about 300 mm of rain each year, receives approximately 60-70% of its water supply from 500 km away in the Owens Valley (Groeneveld, 1990). In contrast, cities located in climates with greater amounts of rain do not depend on regional ground water resources to the same extent. However, when ground water is used as a major

supply, withdrawal can have far reaching impacts on the environment. Typically, the negative ecological impacts resulting from ground water pumping are similar to those described for stream and river diversion. If ground water systems are over pumped, the ecosystems may become decoupled from the ground water and unable to adjust to declining water status. From a management perspective, understanding the safe water withdrawal rates can be difficult because the effects of excessive and unsustainable groundwater development may not be immediately obvious (Cooper et al., 2003). Highly attractive water sources, such as shallow aquifers, are important for maintaining stream flow and associated wetland hydrologic regimes (Cooper et al., 2003). A lowering or depletion of these aquifers can result in changes in vegetation cover (Groeneveld and Or, 1994), and the conversion of streams from perennial to intermittent flows (Cooper et al., 2003). These environmental impacts typically take longer to occur, and usually once these changes have taken place, potentially costly to mitigate or restore. Ultimately, no matter the cause of the ground water shift, the ecosystem will respond in some manner and this response will be displayed most strongly by organisms which are most closely coupled to the groundwater source.

Water Usage of Phreatophytic Vegetation

Meinzer (1927) coined the term phreatophyte (literally “well plants”) to refer to plants with the ability to send roots deeply into the soil and acquire water in the saturated zone. Phreatophytes are subdivided into two categories: obligate and facultative (Smith et al., 1998). Obligate phreatophytes receive their water from the water table (actually the capillary fringe immediately above the saturated zone), while facultative phreatophytes

have the ability to switch water use from the saturated to the unsaturated zone based on conditions of water availability. Non-phreatophytic plants are not deeply rooted and thus take up water within the vadose zone.

The root morphologies of facultative phreatophytes are shown in Figure 1-1 and are typically dimorphic, with both superficial nutrient-acquiring lateral roots and a deeply penetrating tap root (Dawson and Plate, 1996).

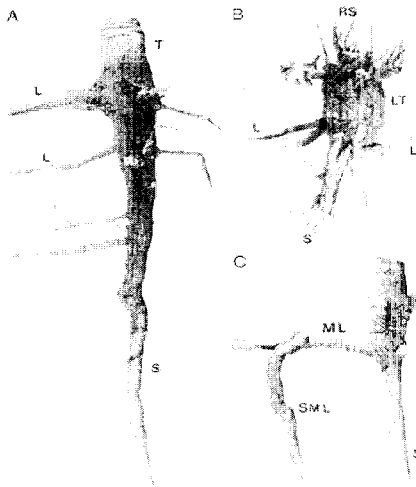


Figure 1-1 A-C. Examples of dimorphic root systems. **A** *Banksia prionotes*, **B** *Grevillea* sp, **C** *Banksia illicifolia*. Figure taken from Dawson and Pate (1996).

In *Banksia prionotes*, a facultative phreatophyte, water uptake occurs by both the lateral and tap roots during the wet season. However, once soil water becomes less abundant during the dry season, this species shifts its water acquisition to groundwater via multiple tap roots (Dawson and Pate, 1996). These same results have also been documented by Donovan and Ehleringer (1994) in the Great Basin. During the summer, plants were

shown to use both deeper soil moisture remaining from winter recharge and shallow soil moisture resulting from summer convective storms. This shift in water acquisition was believed to be beneficial to the plant because it allows for the maintenance of the shallow nutrient acquiring roots during the dry summer when vadose zone soil moisture has been depleted. This also allows the plant to respond rapidly to the onset of autumn rains, before the upper soil is fully wetted (Dawson and Pate, 1996). Furthermore, continuous water acquisition allows for transpiration, carbon assimilation and continued growth to occur during times when shallow-rooted species are forced to cease such physiological processes (Dawson and Pate, 1996).

Obligate phreatophytes acquire most of their water from the saturated zone, although more limited water and nutrient acquisition does occur from shallow soils when they are wet. The root morphology of an obligate phreatophyte such as *Chrysothamnus nauseosus*, contains tap roots that arise from a single stem base which does not support extensive lateral root branching (Groeneveld, 1990). Rooting patterns for obligate and facultative phreatophytes are shown in Figure 1-2. In the Great Basin study carried out by Donovan and Ehleringer (1994), *Chrysothamnus* did not use summer rain (determined by using δD ratios), which suggests that this species lacks active roots in the shallow soil layers. Additionally, *Chrysothamnus* showed the least seasonal change in pre-dawn water potential (Ψ_{pd}), which is consistent with previous reports that this species is one of the most deeply rooted and least water-stressed shrubs in the Intermountain West (Donovan and Ehleringer, 1994). This lack in Ψ_{pd} response suggests that the plant had a consistent water supply throughout the entire study, and was not shifting water uptake in response to incident rainfall events.

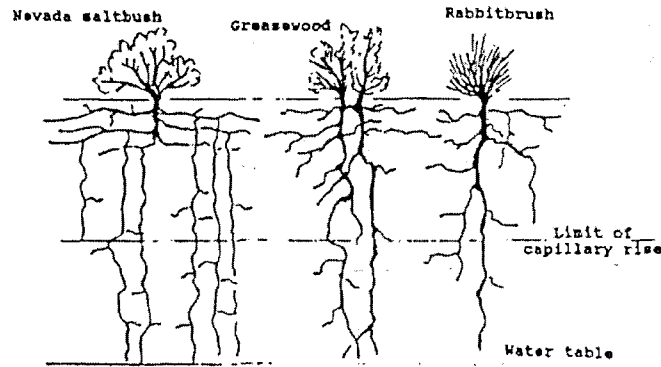


Figure 1-2. Schematic of rooting pattern for the facultative phreatophytes Nevada saltbush (*Atriplex lentiformis*) and greasewood (*Sarcobatus vermiculatus*), compared to the rooting pattern of the obligate phreatophyte rabbitbrush (*Chrysothamnus nauseosus*). Figure taken from Groeneveld (1990).

Tradeoffs exist for phreatophytes that maintain either facultative or obligate status. Facultative phreatophytes have the benefit of being able to switch between deep and shallow water. This allows the plant to use less energy by obtaining water from a shallow source when available. However, the tradeoff is that the plant must use energy (carbon allocation) to maintain a dual root system. In contrast, obligate phreatophytes maintain deep tap roots and a less extensive lateral root system, which allows the plant to maintain contact with the capillary fringe during both the wet and dry seasons. However, they will be more vulnerable to changes in water table depth (Smith et al., 1998).

Water use by phreatophytes varies by species, climate and water availability. The amount of water transpired by phreatophytes has been demonstrated to be enough to cause diurnal water table fluctuations (Loheide et al., 2005), so reasonable estimates of groundwater consumption can be obtained through the analysis of well hydrographs. Using the method of White (1932), where net inflow rate, determined from the water table recovery during the overnight period (assumed zero transpiration), net change in

elevation of the water table over the course of the day, and an estimate of specific yield (defined as the volume of water that a saturated soil will yield by gravity per unit area of soil per unit change in water table elevation) are all used to generate a water usage number (Loheide et al. 2005). They suggest that this method can provide a cost-effective way to describe the water use of phreatophytic plant communities. However, the method does have some limitations, specifically: (1) monitoring wells need to be screened across the water table not just deeper intervals, (2) high resolution and high-accuracy pressure transducers are needed to detect water table fluctuations, (3) the White (1932) method may need to be adjusted to get more appropriate average recharge values for a 24-hour period, (4) the White (1932) method is highly sensitive to unsteady processes such as on/off cycling of nearby pumping wells, and (5) readily available specific yields must be determined carefully in order to avoid error in estimated groundwater ET. It is clear from this list, that some infrastructure is needed to accurately use this method.

Steinwand *et al.* (2006) also demonstrated varying amounts of ground water usage by phreatophytes in Owens Valley CA. The vegetative community was separated into alkali meadows, rabbitbrush meadows, rabbitbrush scrub Nevada saltbush meadow, Nevada saltbush scrub, and desert sink scrub. They concluded that groundwater uptake accounted for 60-81% of ET in the alkali meadows (water table depths 1-3m), 35-67% in the mixed grasses and shrubs (water table depths 2.1-3.2m), and 21-33% of ET in the shrub-dominated sites (water table depths 3.9->5m). The high dependence of alkali meadows on groundwater suggested that such meadows would be very sensitive to a drop in water table (Steinwand et al., 2006). This conclusion was supported by the relationship

shown in Figure 1-3, where increased depth to water was associated with higher ET generated from precipitation relative to groundwater.

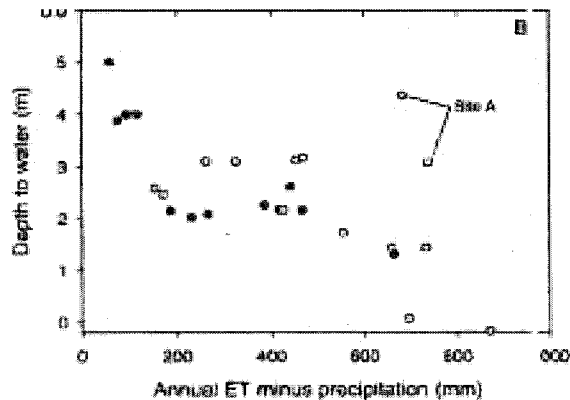


Figure 1-3. Comparison of annual ET as a function of depth to groundwater. Data presented are annual ET minus yearly precipitation. Figure taken from Steinwand *et al.* (2006).

Physiological Response to a Falling Water Table

Plants that depend on ground water sources all have threshold rooting limits, beyond which ground water acquisition is no longer possible. A drop in ground water below this threshold can result in many different types of physiological responses at the leaf, canopy and root levels. One such physiological response at the leaf level, which has been documented as being positively correlated with declining water tables, is declining leaf xylem water potential. In a study on the physiological and morphological response of *Populus deltoides* to ground water pumping, it was found that a rapid decline in the water table resulted in decreased leaf xylem water potential (Cooper et al., 2003).

Similarly, it was shown by Smith et al. (1991) in a streamflow diversion study in Eastern Sierra Nevada that the lowest midday water potential measurements for *Betula occidentalis*, *Populus fremontii*, and *Salix* sp. occurred along stream diverted reaches and away from the stream channel. Decreasing leaf water potential in response to falling water tables is generally associated with decreases in turgor pressure and an increase in osmotic potential, which is a result of concentrating solutes in the cell. As long as the leaf water potential is more negative than that of the surrounding soil, water will continue to move through the plant. However, at some point (species specific), the pressure in the xylem cells may become too negative, allowing air bubbles to form in the xylem leading to embolism, which can severely compromise the plant's survival. To avoid this problem, the plant must decrease its water usage, perhaps by operating at times of the day when environmental demand is not near its maximum values. Kolb and Sperry (1999) demonstrated that *Artemisia tridentata* decreases its water usage during drought to avoid hydraulic failure. They used a transport model (Sperry et al., 1998) based on diminishing safety margins taken from E_{crit} and Ψ_{crit} , which corresponded to critical values of transpiration and plant water potential beyond which hydraulic failure occurs. The degree of water potential control is widely variable and species dependent. For example, Donovan et al. (1996) demonstrated a significant difference in midday water potentials during August for two co-occurring species growing near Mono Lake CA, *Chrysothamnus nauseosus* (-1.8 MPa) and *Sarcobatus vermiculatus* (-4.6 MPa). Such a difference in leaf water potential would suggest that the response and ultimately survivability of these species to a decline in the water table will be drastically different.

A second physiological variable which can be correlated with a drop in the water table is stomatal conductance. Once a plant begins to approach its critical water potential limits it must begin decreasing its transpirational losses to avoid hydraulic failure. By closing stomata during periods of high environmental demand a plant can decrease its overall water usage and avoid dehydration. This strategy is employed by many species with high transpirational demand such as *Populus* trees (Amlin and Rood, 2003) and *Tamarix ramosissima* (Devitt et al., 1997). Smith et al. (1991) demonstrated this strategy in their stream diversion study, where plants on low-flow sites had lower stomatal conductances than on high-flow sites. By changing the duration and time when stomata remain open, the plant can maintain its basic physiological functions with the exception of carbon fixation. Much like water potential, the degree of stomatal control a plant can employ is species specific, with the tightest control typically occurring in drought tolerant species (Amlin and Rood, 2003).

A plant can use two leaf-level mechanisms to survive a change in availability: control over water potential and stomatal conductance. At the canopy level however, the most common mechanism to decrease water usage is to decrease the vegetative surface area. This strategy accomplishes two major goals: (1) it decreases the surface area for transpirational loss and (2) it allows for a reallocation of resources from the canopy to the roots. This response was noted in controlled studies where a reduction in water availability resulted in leaf senescence and increased abscission in riparian cottonwoods (Amlin and Rood, 2003) and a water table decline of more than 1 m resulted in leaf senescence and crown die back in prairie cottonwoods (Scott et al., 1999). The degree of leaf senescence is species specific however, and some species are able to tolerate a much

lower water table decline than others. For example, some Great Basin phreatophytes are known to send roots to 3.6 m depth and therefore these plants may be able to tolerate a greater water table decline (Groeneweld, 1990). For these species, the reallocation of resources from shoot to root will increase the chance for the plant to maintain contact with the declining capillary fringe.

The root-level response to a falling water table is driven mostly by the plant's need to secure reliable quantities of soil water. If the plant is a facultative phreatophyte and soil water significantly declines in the shallow unsaturated zone, then carbon allocation will be directed to the deeper root system to maintain contact with the water table. This was demonstrated by Schwinning and Ehleringer (2001) using a hydraulic soil-plant model. In the model their subject plant increased deeper root biomass as soil water decreased from -0.5 MPa to -3.5 MPa. However, once the soil water was depleted beyond -3.5 MPa (suggesting the plant is not able to actively take up water from the capillary fringe), the subject plant switched to increasing shallow root biomass. In a study conducted in the Owens Valley, however, Groeneweld (1990) described the root systems for three semi-arid shrubs (*Atriplex torreyi*, *Sarcobatus vermiculatus*, and *Chrysothamnus nauseosus*) as decreasing in density with depth. He concluded that for these species an inter-linkage exists between root development and soil nitrogen content, which also decreases in concentration with depth. Furthermore the study highlighted a maximum rooting depth for these species to be about 3.6 m. This number may be site-specific, since *Sarcobatus* roots have been found 19 m below the ground surface (Robinson, 1958). The argument for the 3.6 m limit is that permanent deeply penetrating roots (greater than 3.6 m) would not be likely due to annual water table fluctuations in the

Owens Valley, which would drown the roots and prevent them from developing into permanent structures. Deeply penetrating roots acquire water from the capillary fringe, not from great depths within the saturated zone. Once the water table has been lowered (along with the capillary fringe) roots will begin to grow downward into these unsaturated soil horizons. Plants will extract this deeper water as dictated by their water requirements (Groeneveld, 1990). *Populus* seedlings have been demonstrated to stay in contact with ground water that is declining up to 20 mm/day, whereas 40 mm/day caused reduced growth, and declines greater than 40 mm/day caused plant mortality (Naumburg et al., 2005). The maximum root growth rates of arid shrub and grass species are thought to range between 3 and 15 mm/day (Naumburg et al., 2005). This strategy of allocating carbon to deeper roots comes with some risk, because the chance exists that a recovering water table may create anoxic conditions and subsequent deep root mortality. However, adaptations can occur to reduce the risk associated with this carbon allocation. For example, to adapt to flooding conditions, roots may show altered metabolism (specifically to hypoxia), increased CO₂ tolerance and an increase in the ability to remove ethanol (Naumburg et al., 2005). Furthermore, roots may develop aerenchyma, which increase internal diffusion of oxygen by increasing root porosity (Naumburg et al., 2005). When a water table falls below a depth at which an individual species can access water, that species would be forced to revert to a non phreatophytic status. Plants that maintain phreatophytic status often have highly suberized roots in the unsaturated zone to prevent water loss back into dry soil. Such roots may be slow to respond to increased levels of soil moisture. In an irrigation study of salt cedar on the Virgin River, Devitt et al., (1997)

reported the presence of highly suberized tap roots and that at least four weeks of irrigation were required before significant increase in water use occurred.

Community Level Response to a Falling Water Table

The ability to maintain deep roots comes with high maintenance energy costs typically leading to a root system dominated by a series of lateral tap roots (Darrouzet-Nardi et al., 2006). However, declining water tables may also benefit plants by leaving behind aerated soil profiles which become available for new root exploitation (Naumburg et al., 2005). Declining water tables may also increase the soil volume available for storage of precipitation and hydraulically lifted water, which can increase plant growth and water. Finally, a shallow water table could lead to the development of saline soils, decreasing the overall health of the plant. This can occur in many areas, but especially in semiarid regions where evapotranspiration leaves behind dissolved solutes which can then be leached by rainwater into the active root zone or directly into the groundwater and later taken up by roots reducing plant growth (Naumburg et al., 2005).

At the community level water availability can be a key factor for determining species composition and vegetation cover. Over a thirteen year period, Elmore *et al.* (2003) observed vegetative changes in Owens Valley California. It was found that 51% of the study area showed unchanging vegetation conditions and 19% exhibited a linear decline in live cover during a drought-induced water table decline. The area which remained unchanged was thought to remain stable due to a relatively small amount of anthropogenic disturbance, and the presence of a mixture of phreatophytic and xeric species. The area also experienced a boom of non-phreatophytic exotic species following

the drought, as the invasive species were able to out-compete the native species. Finally, the highly disturbed regions showed live cover changes due to the ability of exotic annuals to respond to precipitation events through rapid seed germination, out-competing natives which were already highly stressed. Although the exotic annuals may die back in subsequent years, the large seed bank would allow them to maintain an advantage over native vegetation under drought conditions (Elmore et al., 2003).

In another community study undertaken in the Owens Valley, environmental factors were investigated across a sharp shrub-herbaceous ecotone (Groeneveld and Or, 1994). Ecotones are areas of transition between adjacent ecological communities and therefore are good study sites for research on factors which determine vegetation change. The ecotone covered a 20 m zone with scrub vegetation consisting of shrub and herbaceous species on one side and a meadow of herbaceous species which lacked shrubs on the other side. It was found that the one abiotic factor varying across the ecotone was depth to the water table. Human disturbances such as livestock grazing, irrigation and fire remained constant, thus the researchers concluded that these factors would have an equal effect across the ecotone. From the data, Groeneveld and Or (1994) determined that shrub exclusion occurred at a water table depth of about 1 m and that saltgrass began to appear at 2.4 m, becoming dominant with decreasing depth to water. The question remained however, as to why shrub exclusion occurred at 1 m. It was hypothesized that poor aeration was most likely not the cause because the shrub rabbitbrush is fairly tolerant to prolonged flooding, and therefore biotic factors such as competition may have been a factor. Groeneveld and Or (1994) concluded that the long term stability of the ecotone (45 years), even in the presence of numerous drought cycles, was because the water table

has been relatively stable. The study showed that changes in the position or existence of woody-herbaceous ecotones, which are known to occur along water table depth gradients, may serve as an indication of relatively large scale long term change, such as water usage for agriculture or municipalities.

Falling water tables can have significant effects on community dynamics. An important ecological question that must be addressed is the impact of falling water tables on changes in species composition. This question was investigated by Scott et al., (2006) who examined the ecohydrological impacts of woody plant encroachment on a flood plain grassland. They did this by examining CO₂ and water vapor fluxes from a grassland, a grassland-shrubland, and from a mesquite woodland. Results of water use showed higher ET rates following full leaf out in the mesquite woodland when compared to the grassland. The higher ET rates were attributed to the ability of the woody trees to access groundwater. This relationship held true through the monsoon season, even though the grassland had higher plant area index (PAI). Woodland ET during the growing season always exceeded that of the shrub and grassland sites. Furthermore, the monsoon rains increased ET in the shrub lands (43%) and grassland (27%), while the woodland ET remained fairly constant, which suggests a limited ability of the grassland and shrubland to access groundwater year round (Scott et al., 2006). Differing water uses were also shown in the water balance. At all sites ET rates exceeded precipitation (P) and storage (ΔS), leading to the use of significant quantities of groundwater (Scott et al., 2006). Grassland showed the least amount of groundwater usage at both the mixed and homogenous sites (even though at the grassland site they had access to groundwater),

whereas the woodland site had greater groundwater usage than shrublands, due to the larger trees and more mature deep roots.

Net ecosystem exchange (NEE) revealed that the greatest carbon uptake occurred at the woodland site, followed by the shrubland site during the pre-monsoon period (early summer). Again, this was most likely due to deep roots and the dry period limiting soil microbial respiration (Scott et al., 2006). The onset of monsoon rains resulted in an initial net loss in CO₂, but the grassland sites soon showed the largest increase in CO₂ uptake. This was mainly caused by the greater effect the available surface water had on the plant water status of the grassland, whereas the woodland had the greatest decrease in NEE during the monsoon (Scott et al., 2006). This was a direct result of the woodland's ability to maintain contact with groundwater, as it was able to acquire CO₂ readily during dry periods when microbial activity in surface soils was low. It was also the result of the accumulation of surface leaf litter which fueled greater heterotrophic respiratory fluxes when the surface soils became moist (Scott et al., 2006).

Based on the water and CO₂ flux data Scott et al., (2006) found that seasonal ET increases with woody-plant abundance, groundwater use increased with the amount of woody plant cover, and CO₂ loss occurred at all sites following a precipitation event, with the greatest response at the woodland sites. These findings suggest that carbon and water cycling in the semiarid Southwest can be fundamentally altered by vegetative change resulting from groundwater alterations. Furthermore, a shift in resource availability (such as the lowering of the water table) alters the relationship between gross photosynthetic and respiratory activities. Finally, a change in vegetation can alter how precipitation

drives these ecosystem processes, which in turn suggests that the relationships between the ecosystem and climate could also be altered (Scott et al., 2006).

Mitigation Associated with Falling Water Tables

Management decisions to address the impacts of water table fluctuations must be tailored to existing species. Floodplain areas consisting mostly of herbaceous perennials will be more sensitive to groundwater decline than are areas containing woody plants (Elmore et al., 2006). Furthermore, the degree of sensitivity will be a function of distance from the water table drawdown region, with greater distances correlating with less water stress. Overall, the reaction of the plant community is really dependent on the water source. In areas where the water table is shallow, vegetation will be highly responsive to variation in groundwater depth, with the sensitivity decreasing as the depth to the water table increases. The highly sensitive response of the plants to the initial water table decrease is most likely physiological; the plants are adapted to a limited range of fluctuation and once that range has been exceeded the response is immediate and significant (Elmore et al., 2006). The decreasing sensitivity past the initial water table decrease is simply an artifact of rooting depth already being exceeded.

If the water table is already deeper than the rooting depth before a draw down occurs, the physiological response should be minimal. In this instance the vegetation is most likely relying on available moisture in the unsaturated zone which is recharged by precipitation and runoff. In the Owens Valley, once the water table dropped below 2.5 m, the correlation between vegetation cover and groundwater fluctuation became

insignificant, while correlations became significant between vegetation cover and precipitation (Elmore *et al.*, 2006).

These responses to both water table depth and precipitation can help give insight into the plasticity of the plant community with regard to water use. Plants with high plasticity will be highly responsive to initial water table decline, and then highly sensitive to precipitation. In contrast species which are fairly inelastic will not be able to respond to changing conditions, and therefore will not show a precipitation response (obligate vs. facultative phreatophytes). As discussed in the previous sections, plasticity will have a direct impact on community changes resulting from an anthropogenic lowering of a water table. In areas where plants depend on shallow ground water, such as alkali meadows in Owens Valley, CA, species may be replaced by competitors such as annuals and deeper-rooted shrub species. Such a shift would eventually result in a decoupling of the vegetation from changes in the groundwater (Elmore *et al.*, 2006), and significantly altering the dominant species composition.

The result of replacing native species with highly competitive invaders due to water table alterations would likely result in an overall decrease in species richness. Here species richness refers specifically to the abundance of species in plant communities. In a study conducted in the Netherlands, Grootjans *et al.*, (2005) showed that the long term effects of drainage of a meadow resulted in an overall decrease in species richness. The effect of drainage on species richness was greatest for the largest water table decline and on shallow rooted species relying on a stable groundwater source. Over the 26-year study, the overall loss of species richness was approximately 45% in the drained meadow, while the un-drained meadow had a 12% decline (Grootjans *et al.*, 2005). The

decline in species richness was apparently due to both water table draw-down and a decrease in nutrient availability. At the population level it was suggested that changes in the ecologic and genetic factors may play a significant role in the survivability of small populations. These genetic factors may include smaller population offspring either being less variable or less viable (Grootjans et al., 2005). Therefore, when management practices are being developed to address the impact of falling water tables, it is important to also look at genetic processes which may accelerate the decline of small populations (Grootjans et al., 2005).

Mitigation associated with water acquisition from shallow groundwater systems should incorporate many different types of plant and community-level indicator signals. Population sizes are one useful indicator since they can give a clear signal of change, even if no consensus about the underlying mechanisms of the population decline (Grootjans et al., 2005). At the leaf level, plant physiological measurements can be used to determine the level of water stress plants are experiencing. At the canopy level techniques such as eddy covariance, and large aperture scintillometry can help to determine water usage by investigating evapotranspiration. Finally, large spatial scale measurements, based on remote sensing, can be used to scale leaf and canopy level measurements to basin wide measurements of evapotranspiration. Failure to incorporate measurements taken at the leaf, canopy, and basin level may result in a misinterpretation of the ecological signals and the formulation of erroneous conclusions. Management decisions based on such conclusions could lead to the accelerated decline of native plant communities.

Dissertation scope

The goal of this research was to examine the water usage of vegetation located in the Great Basin Desert, NV. My research starts from investigating the applicability of using a large aperture scintillometer (LAS) to estimate sensible heat over large path lengths in a semi-arid region, which is an important component for utilizing the energy balance to help close a water balance. This is followed by a sap flow study used to assess the differential water use of *Sarcobatus vermiculatus* located in two separate valleys during the growing season of 2007.

In Chapter 2, I report that sensible heat values obtained from the scintillometer are in good agreement with those obtained from other techniques such as Eddy Covariance. These results suggest that the LAS may be used in semi-arid regions to estimate sensible heat over large pathlengths, which may be vital to the mitigation of water resources located in the desert southwest.

Chapter 3 focuses on the water use of the facultative phreatophyte *S. vermiculatus*. Results from this study show that removing a groundwater source from this shrub can lead to a drastic decline in transpiration. Furthermore, it was demonstrated that these plants have the ability to extract significant water from the vadose zone, and when infiltration from precipitation was prevented flow rates decreased when compared to plants utilizing both precipitation and groundwater.

Sustainable natural water resources is the current focus of many water managers located in the semi-arid southwestern US. It is the hope of the author that this research will provide information needed to aid in the mitigation of groundwater extraction from these valleys while maintaining the natural vegetation.

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CHAPTER 2

ESTIMATING SENSIBLE HEAT IN THE GREAT BASIN, NEVADA USING A LARGE APERTURE SCINTILLOMETER

Abstract

Large aperture scintillometers (LAS) make measuring sensible heat over extended path lengths possible, improving energy balance assessments at the basin scale. An experiment using a large aperture scintillometer and an eddy covariance (EC) tower was designed to compare the measured sensible heat values over different footprints (dictated by the instruments) in a semi-arid high elevation desert. The experiment also included measurements of plant water status, soil water status, and environmental demand. Measurements were taken on four dates, between April and September 2005, at three different locations to investigate spatial and temporal differences in sensible heat between the two measuring devices. LAS sensible heat was corrected for mechanical disturbances using Monin-Obukhov Similarity Theory, and EC sensible heat was corrected using the post-processing program EdiRE. Results indicated good agreement between the LAS and EC for all sites and time periods, with correlation coefficients between 0.85 and 0.98 ($p < 0.001$ for all four dates). As the environmental demand increased, soil moisture declined, leading to a subsequent decline in leaf xylem water potentials and an increase in canopy-to-temperature differentials. Maximum stress

occurred in mid-July, with a slight recovery in early September, which was associated with a decrease in the vapor pressure deficit (VPD) and a slight increase in shallow soil moisture. Increased stress was associated with increased sensible heat during these periods, which was captured with both the EC and LAS systems. Results from this experiment confirm that LAS may be used in place of EC systems to measure sensible heat over longer footprints, which will prove useful in the mitigation of water resources in semi-arid environments. Additionally, measurements of plant water status, soil moisture, and environmental demand were critical in the final interpretation of the data provided by these systems.

Introduction

With increasing population growth in the arid southwestern US and the potential for global climate change, which could alter the availability of water resources in this region, a significant amount of research has been undertaken to better understand water budgets at the watershed and basin levels. Evapotranspiration (ET) is the second largest component, behind precipitation, in the water budget (Glenn et al., 2007). Therefore, accurate estimates of ET are critical for closing the water balance. λE is often assessed using the energy balance approach (Chehbouni et al., 1995; Hemakumara et al., 2003; Gowda et al., 2007):

$$\lambda E = R_n - G - H \tag{1}$$

where λE is the latent heat of vaporization, R_n is net radiation, G is soil heat flux, and H is sensible heat. Two primary methods, eddy covariance (EC) and Bowen ratio, are widely used to assess λE and H ; however, these systems tend to be stationary, allowing for estimates over relatively small foot prints that are dictated by the heterogeneity of the landscape, prevailing wind, and composition of the vegetation (Chehbouni et al., 1999; Hemakumara et al., 2003; Hoedjes et al., 2007). Rarely are these estimates alone sufficient for large-scale water budget estimates, and techniques for scaling these measurements to the basin represent a significant challenge to the scientific community. One technique that has been used to scale sensible heat from Bowen ratio and EC systems to larger spatial scales is the large aperture scintillometer (LAS) (Chehbouni et al., 1999; Meijninger et al., 2002; Hemakumara et al., 2003; Huang et al., 2004; Hoedjes et al., 2007).

Several investigators have demonstrated the validity of the LAS to obtain area-averaged sensible heat values over several kilometers, by comparing LAS output to other measurement techniques such as EC and remote sensing (DeBruin et al., 1995; Chehbouni et al., 1999; Meijninger and DeBruin, 2000; Meijninger et al., 2002; Hemakumara et al., 2003). LAS works by transmitting a signal from 924 LEDs and analyzing the intensity fluctuations at the receiver end. Fluctuations in this context are caused mainly by differences in temperature and humidity along the path length under stable atmospheric conditions. Under unstable conditions, mechanical turbulence in the form of wind can also contribute to intensity fluctuations, which later needs to be corrected using the Monin-Obukhov Similarity Theory (MOST) (Panofsky and Dutton, 1984). LAS measurements allow for an estimate of the refractive index of air (C_n^2) which

can be directly related to the temperature structure parameter (C_T^2) that is needed for a final calculation of H.

Most of the research on LAS has been done in non-arid settings (DeBruin et al., 1995; Meijninger and DeBruin, 2000; Meijninger et al., 2002; Hemakumara et al., 2003) and relatively little research has been done in semi-arid conditions that typify large areas of Nevada. Therefore, the goal of this study was to investigate the validity of using LAS over heterogeneous terrain in a semi-arid region at three sites in the Great Basin desert of Nevada. The study was undertaken in the spring of 2005 and was accomplished by comparing EC sensible heat, corrected using the EdiRE software (University of Edinburgh, 2003), and LAS sensible heat corrected using MOST (Panofsky and Dutton, 1984). Plant, soil and environmental measurements were used to assess temporal and spatial differences along the 1500 m transects measured by the LAS system.

Methods

Site Description

During the spring and summer of 2005, four scintillometer campaigns took place in White River Valley (WRV), approximately 322 km north of Las Vegas, NV. The valley is located in the Great Basin Desert, which is about 306,000 square kilometers and is considered to be the largest US desert. The Great Basin desert is bordered by the Sierra Nevada Range to the west and the Wasatch Range to the east. This cold desert has an annual precipitation of 200-350 mm, most of which occurs as winter snowfall (Weisberg *et al.*, 2007). Average daytime high temperatures during the summer months are approximately 32°C. Vegetation in the basin is typically low and homogeneous, with

four major shrubs occurring at the study sites: *Atriplex confertifolia* (shadscale), *Artemisia tridentata* (big sagebrush), *Sarcobatus vermiculatus* (greasewood), and *Chrysothamnus nauseosus* (rabbitbrush).

Three separate 1500-m transects were established within White River Valley (Figure 2-1).

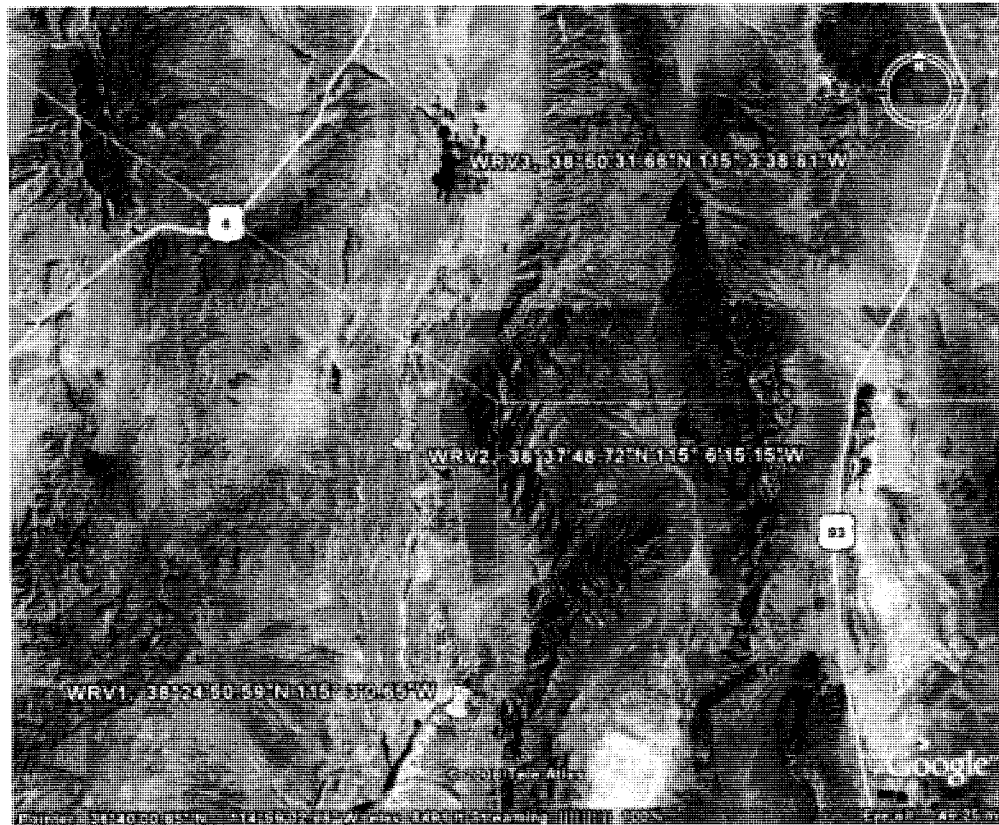


Figure 2-1. Google Earth (Google ®, 2004) image of scintillometer run locations. Runs at WRV1 occurred on 4-14-05 and 9-5-05, WRV2 on 7-19-05, and WRV3 on 6-1-05.

The first transect was established at a site designated as White River Valley 1 (WRV 1, 38 24'50.58"N, 115 03'00.65"W) and is the southern-most site located near the Kirch Wildlife Refuge. Here, the transect ran from east to west. Vegetation at the site was

dominated by *A. tridentata* and *S. vermiculatus*. Percent shrub cover was approximately 62%, and soil texture at the surface was classified as a clay loam. The second transect also ran east to west and was established 24 km to the north at White River Valley 2 (WRV2, 38°37'48.72"N, 115°06'15.15"W). Vegetation at this site contained all four major shrubs. The percent cover was approximately 55%, and the surface soil was classified as a loam. Finally, the White River Valley 3 (WRV3, 38°50'31.66"N, 115°03'38.80"W) transect was established 24 kilometers north of WRV2, west of the town of Lund in a north to south configuration. Again, vegetation at this site contained all four major shrubs, and percent cover was approximately 41%, with a loam soil texture at the surface.

Instrumentation

As part of a larger study, an eddy covariance tower (EC) and weather station (Campbell Scientific Inc., Logan UT, USA) were installed during the spring and summer of 2004 at the WRV 1 site to estimate the components of the energy balance. The EC system was mounted on a 3-m galvanized steel tripod, which included a 3D sonic anemometer (model CSAT3) mounted one meter above the canopy, an open-path infrared gas analyzer (model CS7500) mounted one meter above the canopy, a REBS net radiometer (model Q7.1), two soil heat flux plates (model HFP01SC), two soil thermocouple probes (model TCAV-L), two soil water reflectometers (model CS616), and a combination air temperature/relative humidity probe (model HMP45C-L). Data were stored on a datalogger (model CR5000) equipped with a 1 Gb memory card. Both the EC and weather stations were moved to the appropriate site during the scintillometer measurement dates and centered within a 25x25 m plot. Fluxes were later calculated

offline and were corrected using EdiRE (University of Edinburgh, 2003). This technique was used on all data and allows for the following corrections: despiking and low pass filtering, sonic temperature path correction, sonic flow distortion, rotating velocity signals, sonic temperature density correction, highpass filtering signals, frequency response corrections, sonic temperature correction and density corrections.

All corrections were made to the 10-Hz data (time interval of 0.1 second) prior to calculating 30-minute averages. Fluxes were then calculated using the averaged data. More details on the correction procedures can be found on the University of Edinburgh website: <http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe>.

Two micrometeorological stations were installed on either side of the EC tower (direction was dependent on how the path length was set at individual sites) about 375 m from both the LAS source and receiver. These stations included a net radiometer (model Q7.1), two REBS soil heat flux plates (model HFT-3), and two soil water reflectometers (model CS616). These stations provided an assessment of available energy along the path length.

A large aperture scintillometer (model BLS 900, Scintec, Tubingen, Germany) was used to estimate sensible heat along a path length of 1500 meters (Figure 2-2). The receiver and transmitter were both kept approximately nine meters above the ground surface. The transmitter was mounted on a large 10-meter steel pole with stabilizing guy wires, anchored with stakes driven to a depth of one meter, while the receiver was placed on a telescopic boom lift.

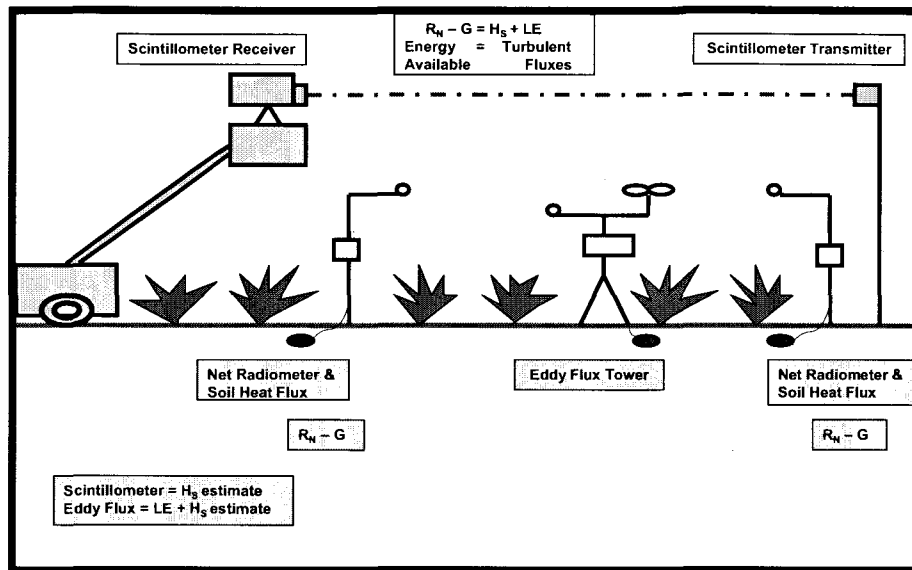


Figure 2-2. Schematic of scintillometer run experimental set up. The transmitter and receiver were set up at either end of the 1500 meter transect. The EC station was centered and two micro-met stations were installed 750 meters on either side. The EC station measured all the energy balance components, while the micro-met stations measured net radiation and soil heat flux and the scintillometer measured area averaged sensible heat.

The path length was set so that the LED transmission from the transmitter would pass over both the eddy flux and micrometeorological stations.

Soil, environmental, and plant physiological measurements

Field measurements were used to evaluate environmental demand and plant water status of major shrubs during each scintillometer run. Three shrubs of each species were chosen randomly at each of the transmitter, the EC system, and the receiver locations during the morning, midday, and evening periods to assess spatial and temporal changes in plant water status. Measurements included: leaf xylem water potential (Scholander Pressure Bomb, PMS Instruments, Corvallis OR, USA) and leaf temperature (Infrared Thermometer, Cole Parmer Instruments, Vernon Hills IL, USA). Soil measurements included surface temperature, and volumetric soil water content at 5-cm depth (model

HH2 Moisture Meter, Delta-T Devices, Burwell Cambridge, UK). Field level normalized difference vegetation index (NDVI) data were acquired with a PP Systems Unispec (Amesbury MA, USA) field spectrometer.

Data were taken along the scintillometer path approximately every 7 m by holding the Unispec at 1.25 meters above ground surface, resulting in a field-of-view diameter of 0.6 m. A total of 100 spectra measurements at 1-m intervals were also acquired along two perpendicular transects (50 spectra per transect) within the presumed footprint of the EC tower. The Unispec fiber tip was held approx 1.25 m above ground surface, yielding a field of view of approximately 0.6 m.

The Scintillation Method

The LAS consists of a transmitter, receiver, and signal processing unit (SPU) which were installed at a user-specified height (z_{LAS}) and separated by a user-specified path length. The transmitter was set at 5 Hz frequency. The receiver collimates the incoming radiation onto 2 photodiodes, one which senses turbulence-induced fluctuations and one which is used to aid alignment. The SPU demodulates and digitizes the received signals and stores data on a microprocessor card. The SPU also allows for communication to a PC via a serial interface.

As the light (880 nm wavelength) travels along the path length, turbulence in the atmosphere causes a degree of scatter. The observed fluctuations in radiation can be expressed as the structure parameter of the refractive index of air (C_n^2). This relationship was demonstrated by Wang et al., (1978),

$$C_n^2 = 4.48\sigma_{\ln A}^2 D^{7/3} L^{-3} \quad (2)$$

where $\sigma_{\ln A}^2$ is the observed intensity of the radiation fluctuations, D is the aperture diameter, and L is the pathlength.

In a stable atmosphere, the fluctuations in the atmosphere are generated by temperature (T) and humidity (q), which suggests that C_n^2 can be related to the structure parameters of temperature (C_T^2) and humidity (C_q^2) (Meijninger et al, 2002). DeBruin et al. (1995) indicate that when used under dry conditions where the Bowen ratio (B) exceeds unity during the daytime, C_q^2 can be ignored and Equation 2 can be used to relate C_n^2 to C_T^2 ,

$$C_T = \frac{C_n T^2}{0.78 p} 10^6 \quad (3)$$

where T is temperature in K, and p is the atmospheric pressure in Pa.

The sensible heat flux (H) from the LAS is generated under the assumptions of a stable atmosphere and thus is referred to as H free convection (H_{fc}). However, during windy experimental runs, the measurement of H is also influenced by mechanical disturbance and a correction must be made to H_{fc} to improve accuracy. The Monin-Obukhov Similarity Theory (MOST) uses C_T^2 and wind speed data through an iterative series of dimensionless equations to generate H_{MOST} , where C_T^2 is a universal function (f_T) of $(z-d)/L$ (Meijninger and DeBruin, 2000). The function was described by Wyngaard et al. (1971) for unstable conditions as:

$$\frac{C_T^2(z-d)^{2/3}}{\theta_*^2} = f_T\left(\frac{z-d}{L}\right) = C_{T1}\left(1 - C_{T2}\frac{z-d}{L}\right)^{-2/3} \quad (4)$$

where the temperature scale $\theta_* = -H/Pc_p u_*$, L is the Obukhov length, z is the height, d is the displacement height, P is the air density, c_p is the specific heat of air at constant pressure, u_* is the friction velocity, and C_{T1} and C_{T2} are empirical constants. DeBruin (1993) defined C_{T1} and C_{T2} as 4.9 and 9.0, respectively, and L can be defined (DeBruin et al., 1995) as:

$$L = -\frac{T u_*^2}{kg \theta_*} \quad (5)$$

Finally, an independent measurement of u_* can be calculated using the standard flux-profile relationship (Panofsky and Dutton, 1984) as:

$$u_* = \frac{\kappa u}{\ln\left(\frac{z-d}{z_0}\right) - \varphi_m\left(\frac{z-d}{L}\right) + \varphi_m\left(\frac{z_0}{L}\right)} \quad (6)$$

where φ_m is the Businger-Dyer correction and κ is the von Kármán constant. Solving Equations 4, 5 and 6 iteratively allows for the generation of H_{MOST} under unstable conditions.

Results

Energy Balance Components

Energy balance components for the four measurement dates are shown in Figure 2-3.

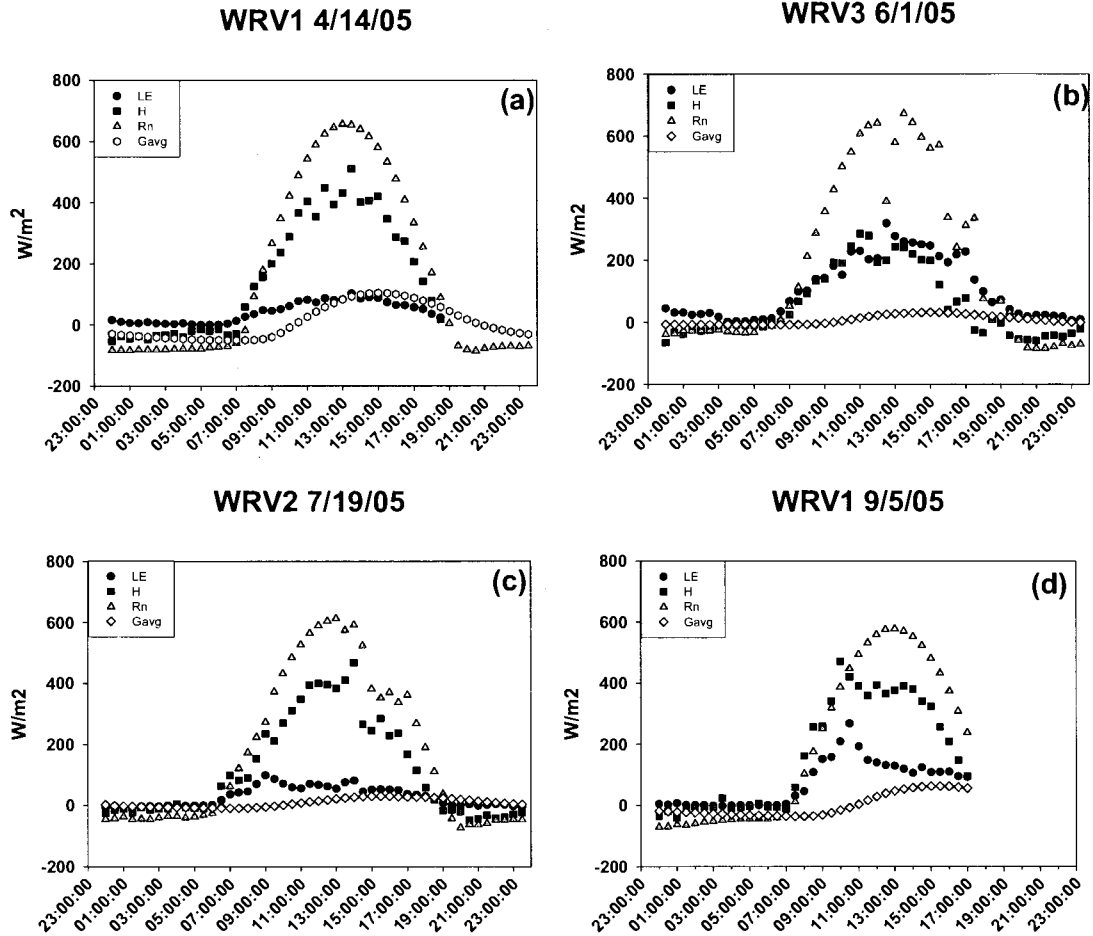


Figure 2-3. 30 minute average diurnal energy balance components taken from the Eddy Covariance station during four different measurement periods (a) energy balance at WRV1 on 4-14-05 with 62% cover; (b) energy balance at WRV3 on 6-1-05 with a 41% cover; (c) Energy balance at WRV2 on 7-19-05 with a 55% cover; (d) energy balance at WRV1 on 9-5-05.

During the 4-14-05 measurement period (Fig. 2-3a), net radiation peaked at midday at 656 W/m^2 . Almost all energy was partitioned into sensible heat with a maximum of 509 W/m^2 occurring at 13:30. Latent heat on this day was low, with a maximum value of only 103 W/m^2 , also occurring at 13:30. *A. tridentate*, and evergreen, was the only dominant shrub that possessed fully developed leaves. A consequence of this was revealed in how the energy was partitioned. Because many of the plants had yet to produce leaves, λE , and thus ET was low, as H dominated the energy balance. Subsequently the Bowen ratio on this day had a maximum value of 5. Furthermore, a significant amount of soil heat flux was measured during midday, maximizing at 104 W/m^2 .

During the 6-1-05 measurement period (Fig. 2-3b) net radiation peaked at midday at 673 W/m^2 although R_n decreased at 12:30 down to 330 W/m^2 with a corresponding drop in λE and H, which was attributed to passing cloud cover. Plants during this measurement period had fully leafed out and therefore the incoming energy was partitioned less into H and more into λE when compared to the 4/14/05 measurement date. The greater λE also contributed to less ground conduction (G), which registered a maximum value of 32 W/m^2 .

As measurements moved later into the summer (7-19-05, Fig. 2-3c) maximum R_n remained about the same but the energy was again partitioned mostly into H, with λE decreasing. This partitioning was primarily due to plants experiencing greater water stress as environmental demand was high (daily potential ET on 6-5-05 was 6.8 mm and on 7-19-05 it was 8.6 mm) and vadose zone soil moisture had decreased significantly (Fig. 2-4). In Fig. 2-3c, H and λE were similar at 09:00, but afterwards λE decreased as H increased. Soil heat flux during this time period remained small, with a maximum value

of about 30 W/m^2 . Differences in G between this period and the measurement period on 4/14/05 may be attributed to a change in surface albedo associated with declining soil moisture, an important parameter affecting surface radiation budgets (Li *et al.*, 2008).

The highest soil water content at 5-cm depth occurred during the 4-14-05 campaign (Figure 2-4). Soil moisture in early spring was highest due to a contribution of winter

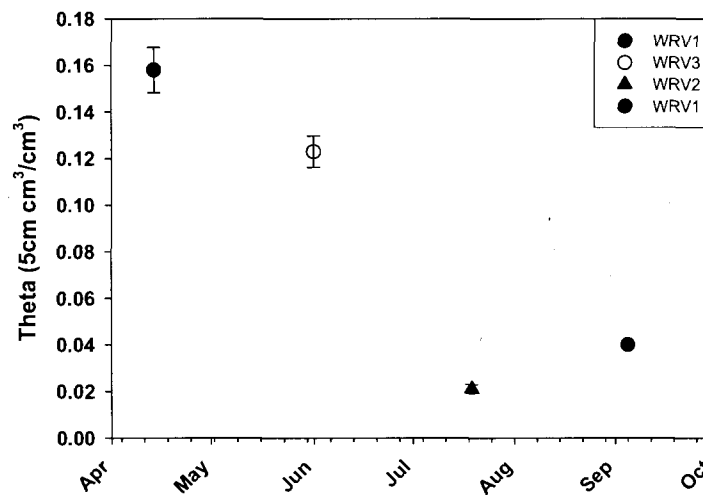


Figure 2-4. Average volumetric water content ($\pm 1 \text{ SE}$) at 5-cm depth measured on each scintillometer campaign.

rainfall, low environmental demand and low plant activity. These wetter soils were visually darker in color, which would have a lower surface albedo, leading to a higher soil heat flux, as shown in Figs. 2-3. However, as the growing season progressed, plants readily used this shallow water and by 7-19-05, the volumetric soil water content at the surface (0-5 cm) was only $0.02 \text{ cm}^3 \text{ cm}^{-3}$ (Figure 2-4). Thus, the results are consistent

with drier soils with higher surface albedo, which reflects more energy back into the atmosphere, reducing G.

The final scintillometer campaign occurred on 9-5-05, revealing similar R_n values as recorded on the other monitoring dates, with λE increasing with a corresponding decrease in H during the morning hours. The rise in G during the 9-5-05 campaign, when compared to G during the 7-19-05 campaign, was most likely related to the increase in soil moisture leading to a decrease in surface albedo (soil moisture differences between the two runs was 2% and was statistically significant at $p = 0.05$). However, this difference may have been a result of differences in site characteristics rather than precipitation. At WRV1 (9-5-05) the percent cover was 62% with a classified soil of clay loam. In contrast, at WRV2 (7-19-05) the percent cover was 55% with mostly a loam soil. Therefore, the higher percent cover and higher proportion of clay in the soil could have led to a lower surface albedo that would result in more incoming short wave radiation available for partitioning into energy balance components (Zvomuya et al., 2008).

Plant Measurements

To further understand the partitioning of energy during the scintillometer runs, plant water status was investigated by looking at midday leaf xylem water potential (Ψ_L). Figure 2-5 shows Ψ_L for all experimental run dates. On 4-14-05, the plants did not show signs of water stress, as midday Ψ_L was approximately -2 MPa (Fig. 2-5a). On this day λE was low because many species had not fully leafed out. By 6-1-05, Ψ_L was still approximately -2MPa (Fig. 2-5b) with fully developed canopies. Higher λE values associated with the more positive Ψ_L values indicated that the plants were transpiring

under non-water stress conditions (Fig. 2-3c). By 7-19-05, Ψ_L had reached approximately -5 MPa (Fig. 2-5c) and λE had dropped significantly, reflecting water-limiting conditions. Figure 2-4c revealed a rise and fall of λE around 09:00 on 7-19-05, suggesting that under water limiting conditions the plants in this study were most active during lower environmental demand periods. On 9-5-05, λE increased when compared to 7-19-05 even though Ψ_L remained at approximately -5 MPa (Fig. 2-5d). It is important to note here that

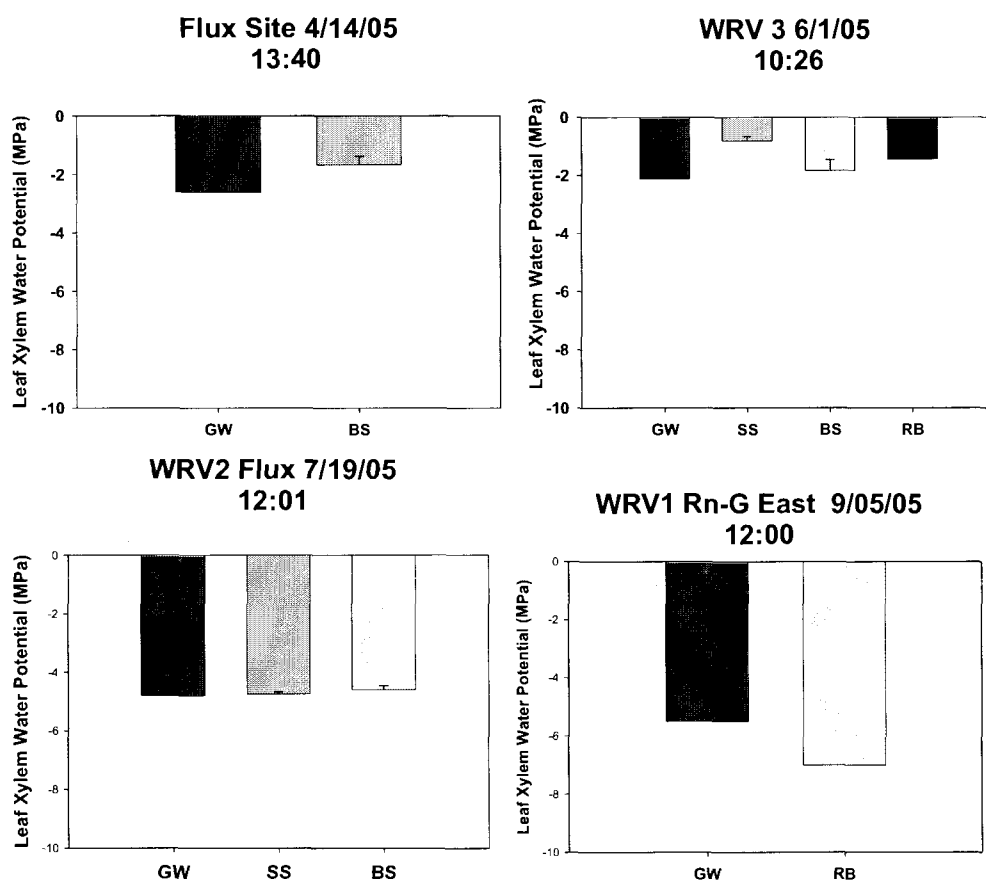


Figure 2-5. Average midday leaf xylem water potentials (Ψ_L) (± 1 SE) on the four scintillometer dates for Greasewood (GW), Shadscale (SS), Bigsage (BS) and Rabbitbrush (RB).

the dominant species at all sites was *S. vermiculatus*, which is capable of actively transpiring at Ψ_L values at and beyond -5 MPa. In a study by Sperry and Hacke (2002), xylem vulnerability curves were generated for eight Great Basin shrubs, showing the percentage loss in xylem conductivity (PLC) as a function of decreasing xylem pressure. Using the approach by Sperry and Hacke (2002) on the *S. vermiculatus* at our sites, a 65% PLC was estimated at -5 MPa, which was the second lowest for all shrubs, suggesting that *S. vermiculatus* is highly tolerant of low soil water potential and can continue to function even under water limiting conditions.

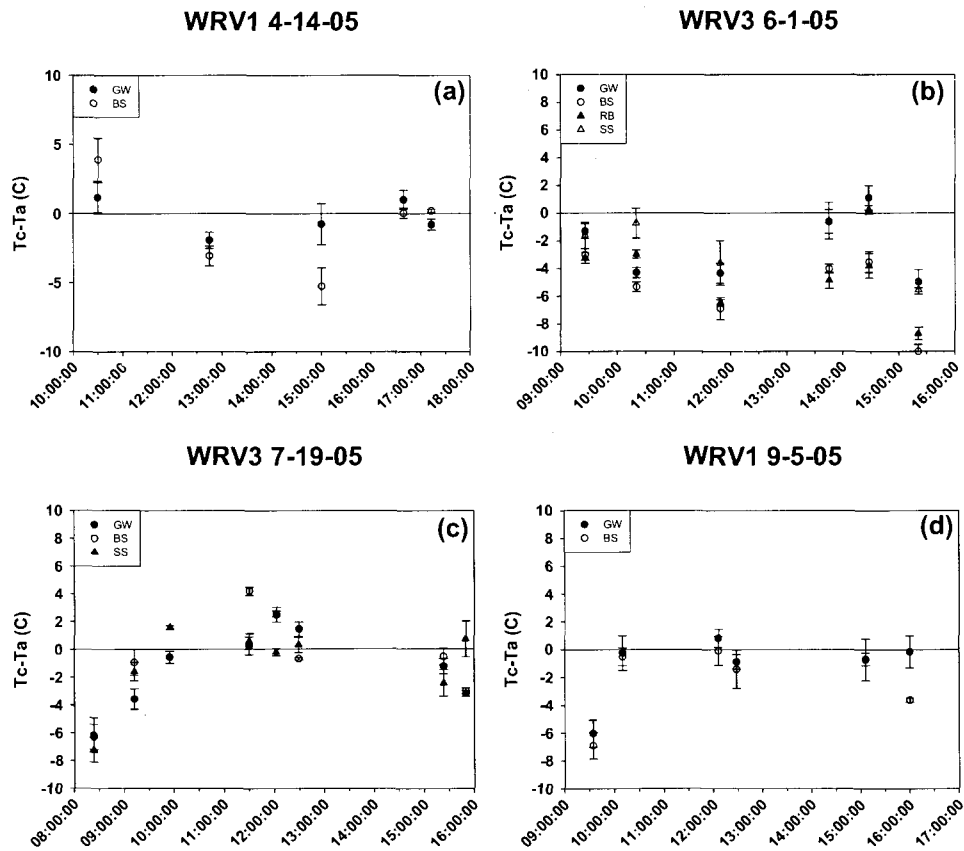


Figure 2-6. Canopy and air temperature differences ($T_c - T_a$) (± 1 SE) for the four scintillometer run dates for Greasewood (GW), Shadscale (SS), Bigsage (BS) and Rabbitbrush (RB).

Figure 2-6 shows canopy and air temperature differences ($T_c - T_a$) for each run date. The difference between canopy and air temperature can be used as an indicator of stress (Testi et al., 2008). When the plant is not water stressed, $T_c - T_a$ often is negative because stomata are open and leaves are cooled by transpiration. However, when the plant is stressed and stomata begin to close $T_c - T_a$ becomes positive. In Fig. 2-6a (4-14-05), only data for *A. tridentata* is shown because *S. vermiculatus* had not yet developed a full canopy. With the exception of the first value, all others were either close to 0 or negative, suggesting low levels of plant water stress. Time of day was shown to affect the measurement. For example, at 10:30 the temperature was 15°C, R_n was approximately 500 W/m², transpiration was low and $T_c - T_a$ was positive. By midday the temperature had risen to 20°C, R_n was close to 700 W/m², and transpiration was higher leading to a reduction in canopy temperatures.

In Fig. 2-6b the majority of $T_c - T_a$ data (6-1-05) for all four species on this day were below zero. These negative $T_c - T_a$ values, in conjunction with the highest Ψ_L values (Fig. 2-5b), confirmed that plants on this day were not water stressed. The negative dip occurring during midday was most likely the result of evaporative cooling associated with enhanced transpiration.

Figure 2-6c shows $T_c - T_a$ on 7-19-05. During time course of this date, the data approached a bell-shaped curve, with positive values occurring during midday when environmental demand was highest, and transpiration (LE) was relatively lower (Fig. 2-3c). These higher $T_c - T_a$ values, measured in conjunction with more negative Ψ_L values (Fig. 2-5c), suggested greater levels of water stress.

Finally, Fig. 2-6d reports the T_c-T_a data for 9-5-05, which represented a time period toward the end of the growing season, but also when soil moisture was elevated due to late summer precipitation. All T_c-T_a values measured on this day were either negative or close to zero with maximum transpiration occurring earlier in the morning.

Assessment of plant response within the footprint of the EC tower and LAS transect

The NDVI was calculated for all field spectra along the 1500-m transect and compared with measurements confined to the center EC tower location. The data are summarized in Table 2-1.

Table 2-1. Summarized scintillometer transect and EC tower footprint NDVI data taken during four scintillometer runs.

Date	Location	Mean	Maximum	Minimum	Std. Dev	Variance
4-14-05	Transect	0.156	0.436	0.056	0.089	.008
6-1-05	Transect	0.293	0.724	0.049	0.166	.028
7-19-05	Transect	0.185	0.513	0.055	0.104	0.011
9-5-05	Transect	0.232	0.639	0.017	0.149	0.022
4-14-05	Footprint	0.147	0.463	0.064	0.064	0.004
6-1-05	Footprint	0.304	0.715	0.057	0.149	0.022
7-19-05	Footprint	0.140	0.511	0.059	0.083	0.007
9-5-05	Footprint	0.212	0.538	0.067	0.136	0.019

On 4-14-05, NDVI data taken along the transect and within the EC tower footprint had the lowest mean, lowest standard deviation, and lowest maximum values. Results were consistent with the partial leaf cover of *S. vermiculatus*, which accounted for 50% of the total percent cover at WRV1 when the plants were fully leafed out. Whereas on 6-1-05, NDVI assessed from the transect and footprint had the highest mean and highest maximum values, as all species at this site had fully leafed out and were operating under

non-water stressed conditions. The standard deviation for this date was also highest, which was influenced by the larger differences in NDVI values among bare soil and differing plant canopy targets along the transects. Data collected on 7-19-05 represented a water-stressed time period and had the second lowest mean and maximum NDVI values. Finally, data taken on 9-5-05 represented a period in which environmental demand decreased and soil moisture increased in response to late summer rainfall leading to less stressful conditions. On this day, the mean and maximum NDVI values were larger than measured on all other dates except for 6-1-05. The variance in NDVI associated with all run dates was less than 0.03 for the transect and the EC tower footprint. The ratio of the mean NDVI from the EC tower footprint divided by the mean NDVI of the transect was 0.94, 1.04, 0.76, and 0.91 for the four measuring periods. Only in the case of measurements taken on 7-19-05, associated with maximum stress conditions, would the NDVI data suggest greater variation in plant response between the scintillometer transect and the EC tower footprint areas.

Meteorological Stations

Half-hour averages of R_n and G were taken from the EC station and two micrometeorological stations located midway between the LAS source and receiver and the EC station. The available energy was calculated as $R_n - G$, and values were plotted for the three different locations in Fig. 2-7. Spatial differences in available energy along the transect were small and not significant at $p > 0.05$. Data from other campaigns were not obtained due to a series of instrument malfunctions on the micrometeorological stations.

Sensible Heat Comparison

Figures 2-8 a-d show a comparison of half hour averages of sensible heat from the large aperture scintillometer (H_{LAS}) and the eddy covariance station (H_{EC}) for the four scintillometer runs. On 4-14-05, sensible heat measurements were only made from 14:00 until 18:00 due to instrumentation error. An excellent correlation was obtained between the EC and LAS methods, with an $r^2 = 0.98$ ($p < 0.001$). Maximum H_{LAS} on this day was 330 W/m^2 , while maximum H_{EC} was 420 W/m^2 , resulting in a slight deviation from the 1:1 line by H_{LAS} as H_{EC} became larger.

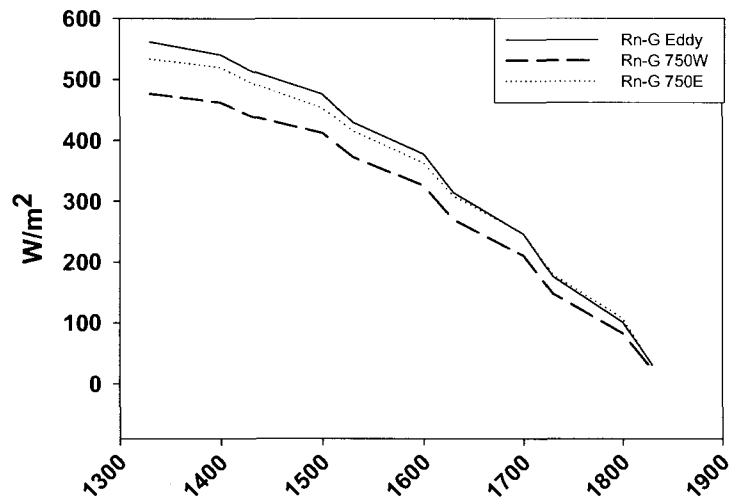


Figure 2-7. Available energy represented by Rn-G for three locations along the WRV1 transect on 4-14-05. The EC station is located 750 m from the receiver and transmitter, and the micro-met stations are located midway between the EC tower and the source and receiver of the LAS. Values represent half hour averages. Differences are non-significant at $p > 0.05$.

Figure 2-8b shows the comparison between H_{EC} and H_{LAS} at WRV3 on 6-1-05. Good correlation was again demonstrated ($r^2 = 0.85$, $p < 0.001$). Measurements on this day occurred from 11:00 until 17:00. Sensible heat fluxes measured using both LAS and EC were the lowest for all four campaigns. Maximum H_{EC} was 285 W/m^2 and maximum H_{LAS} was 265 W/m^2 . Once again there was a slight deviation from the 1:1 line for H_{LAS} as H_{EC} became larger, though this difference was not as pronounced as observed on 4-14-05.

Results from WRV2 on 7-19-05 are shown in Fig. 2-8c. Comparison between the H_{EC} and H_{LAS} were good ($r^2 = 0.85$, $p < 0.001$). Measurements were from 08:00 until 18:00. Maximum H_{EC} was 467 W/m^2 and maximum H_{LAS} was 340 W/m^2 . Again, a slight deviation from the 1:1 line was seen on 7-19-05 for H_{LAS} as H_{EC} became larger.

Finally, results from WRV1 on 9-5-05 are shown in Fig. 2-8d. The correlation during this measurement period was again good ($r^2 = 0.89$, $p < 0.001$), and measurements were taken from 1130 h until 1630 h. Maximum H_{EC} was 393 W/m^2 and maximum H_{LAS} was 376 W/m^2 , with a deviation from the 1:1 line as H_{EC} became larger.

Discussion

The LAS has recently been shown to be a powerful tool for estimating area averaged sensible heat fluxes over long path lengths under both homogenous and heterogeneous conditions. This technique can be used to improve energy balance closures and validate satellite and model estimates of sensible heat flux. However, few examples have been reported where LAS has been used over a heterogeneous terrain in a semi-arid region (Chehbouni et al., 1999 and Ezzahar et al., 2007).

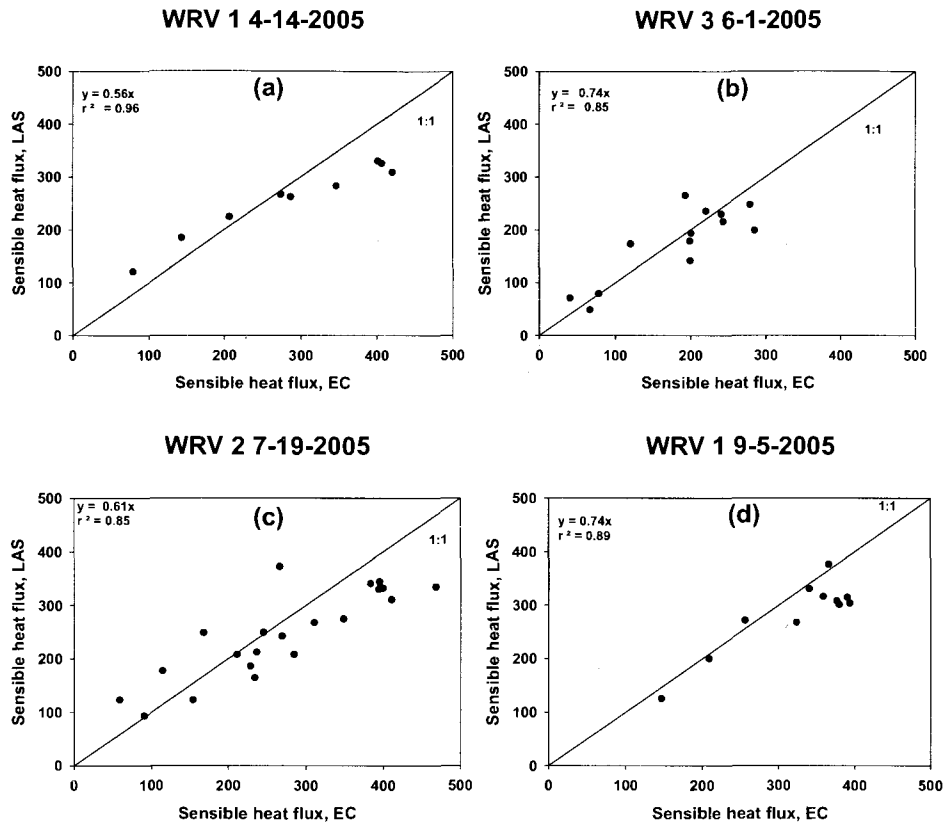


Figure 2-8. Comparison of 30-min measurements of sensible heat taken from the LAS and EC system for four different measurement periods: (a) 4-14-05, (b) 6-1-05, (c) 7-19-05, (d) 9-5-05. Regression analysis for each date is shown in the upper left hand corner of the graph.

Results from this study suggest that the use of LAS and EC methods can provide similar estimates of sensible heat flux over heterogeneous terrain such as found at our field sites in the Great Basin, NV. The inclusion of plant, soil, and atmospheric measurements served to provide additional information on site-specific conditions under which the LAS and EC systems were operating, and they corroborate the differences seen in both measurements over the course of a late spring to fall period. When LAS measurements were taken during unstable daytime periods, the use of MOST corrected H provided good correlations of sensible heat to those measured with the EC system

(EdiRE corrected). However, it is important to note that the degree of heterogeneity in the footprint related to percent cover, plant water status, soil conditions, and environmental demand can all have direct effects on this correlation. Additionally, comparisons between H free convection (H_{fc}) and H_{EC} showed a slight improvement over H_{MOST} and H_{EC} ($r=$ 0.97, 0.86, 0.91, and 0.93, $p<0.001$ for 4-14-05, 6-1-05, 7-19-05, and 9-5-05 respectively for H_{fc} vs. H_{EC}), though no literature was found to support using it in place of H_{MOST} during unstable daytime periods, and therefore it was omitted.

Measurements taken on 4-14-05 at WRV1 had the highest correlation between H values estimated with the EC and LAS systems. This site contained only two dominant shrubs, with *S. vermiculatus* not yet possessing a full canopy (average NDVI = 0.156). Leaf xylem water potentials during this time were approximately -2 MPa, while T_c-T_a values were close to zero throughout the day, and soil water at the surface was close to 0.15, which indicated non-water stress conditions. The high correlation on this day may reflect the homogeneity of the canopy during the experimental run, with the majority of available energy partitioned into sensible heat. Furthermore, more open canopies would allow for a more uniform distribution of surface soil moisture, and a more uniform evaporation component due to surface heating. Canopy density can create micro-climate conditions along the path length that can affect properties such as surface albedo, latent heat, and sensible heat (Olchev et al., 2007). Therefore, the higher homogeneity on this day may have contributed to similar sensible heat flux values being measured at the two different scales.

The effect of soil moisture heterogeneity on sensible heat flux measured by different instruments has been examined by Hoedjes et al. (2007). In their study, sensible

heat flux comparisons between EC and LAS methods were carried out over dry conditions, during an irrigation event, and following an irrigation event. They found that differences in instrument footprints decreased correlation as conditions moved from dry to wet. Finally, we noted in this study that the highest correlation between H_{EC} and H_{LAS} occurred on a day when only afternoon data were available (14:00-18:00). Therefore, we reexamined the data for this same time period for all other campaigns to determine if the correlation was influenced by a temporal factor. It was found, however that although afternoon sensible heat flux comparisons did slightly improve the correlations on 6-1-05 and 9-5-05, afternoon comparisons decreased the correlation for 7-19-05 ($r^2 = 0.87, 0.85,$ and 0.52 respectively; $p < 0.001$). Therefore, the data show that restricting data to afternoon periods was not a defining factor for the higher correlation observed on 4-14-05.

All of the sites possessed excellent fetch (measured in km), which would minimize any significant amounts of localized advection. Other studies have described experiments where the H_{LAS} was higher than the H_{EC} throughout their measurement period. Because the footprint of the scintillometer is much greater than that of the EC system, DeBruin et al. (2005) and Hoedjes et al. (2007) attributed the differences in H to advective heat from adjacent areas. However, in our study the highest H values were associated with the EC. These higher H estimates may be a result of the differences in path lengths between the systems. The LAS is calculating an area average over a longer footprint that may have greater heterogeneity which could cause differences in sensible heat amounts when compared to the EC station. We conclude that sensible heat flux can be accurately estimated with a LAS over heterogeneous terrain in a semi-arid

environment, especially at scales larger than can be assessed with the standard EC approach. This system may allow researchers to have field validation of satellite atmospheric models used to assess water balances at landscape levels. However, additional field validation involving the assessment of soil plant and atmospheric parameters within the footprint of the LAS are highly recommended.

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CHAPTER 3

INVESTIGATING WATER USE IN A GREAT BASIN PHREATOPHYTE USING SAP FLOW

Abstract

Quantifying the water use of phreatophytes in the Great Basin is an essential component in the mitigation process for groundwater pumping in Spring Valley and Snake Valley, NV. Over the past five years, evapotranspiration (ET) in these valleys has been estimated using a series of Eddy Covariance (EC) stations. However, we are unaware of any research that has been conducted in these valleys that has examined how water uptake is partitioned between vadose and groundwater sources. This experiment was designed specifically for the facultative phreatophyte greasewood (*Sarcobatus vermiculatus*). Three treatments were imposed: True Control (TC), Infiltration Prevention (IP), Severed Tap (ST) and Severed Control (SC). Greasewood plants were fitted with stem flow gages and were monitored during the summer growing period of 2007. It was found that the ST treatment had the strongest response to altering available water, by having the lowest flow rates across all measurement periods (average flow of 2977 g/d/cm²). A series of leaf/canopy plant measurements revealed that ST had significantly lower tissue moisture and chlorophyll index when compared to the TC and IP treatments, which eventually recovered later in the growing season. Additionally, canopy air

differentials were higher in the ST group during June, and xylem water potential was significantly lower until later in the growing season when the TC and IP groups began to experience greater water stress. In both valleys, differences in plant physiological measurements between TC and IP were small. Differences in flow rates between the TC and IP treatments were largely dictated by available moisture in the vadose zone. At site SV 1 flow rates in the TC treatment became higher following a series of rainfall events (with the exception of the last measurement period when large variability affected statistical significance). The average IP flow at SV 1 was 9567 g/day/cm², while the ST average flow was 2977 g/day/cm². Isotopic analysis revealed deuterium signatures in stem exudation and transpiration capture most like the signatures of collected rainfall. At site Snk 2, a thicker vadose zone may have affected sap flow rates, as both TC and IP showed an increase in sap flow rates throughout the growing season. Additionally, sap flow rates in the TC treatment were significantly higher than IP only during the month of June. This may have been a result of a delayed precipitation effect dictated by soil texture. Results from this study suggest that these phreatophytes depend on both vadose zone moisture and groundwater. However, sap flow rates were affected much more negatively when the groundwater component to available water was removed, compared to when rainwater infiltration was removed.

Introduction

Population growth, coupled with global climate change, has focused greater attention by the scientific community on water resource issues. In particular, cities located in the arid and semiarid southwestern US are now facing the reality of demand

for fresh water resources exceeding their supply (Barnett et al., 2008). This has caused water managers to employ several water saving practices such as: irrigation with reuse water, irrigation restrictions, removal of high water using ornamentals and turf grass, and xeriscape landscaping. These practices have proved somewhat successful given that irrigation alone can account for 40-70% of a household's water use (St. Hilaire et al., 2008). A hydrologic drought in the Colorado River basin has subsequently led to water levels in Lake Mead dropping so drastically that the lake is currently only half full (Levi, 2008). This is mainly due to falling snow pack levels in the Rocky Mountains that feed the Colorado River system. It has been predicted that the Colorado River will experience a decrease in flow of 10-30% over the next 30-50 years (Barnett & Pierce, 2008). This translates into a 10% probability that Lake Mead and Lake Powel will go dry by 2013 and a 50% chance that they will be gone by 2021 under current water allocation practices.

Water allocation from the Colorado River system is based on a compact signed by all 7 basin states in 1922, where 7.5 million acre-ft/year are allocated to the Upper Basin states (Wyoming, Utah, Colorado, and New Mexico) and 7.5 million acre-ft/yr are allocated to the Lower Basin states (Arizona, Nevada, California). Nevada receives 300,000 acre feet per year with additional water withdrawals based on return flow credit (Deacon, 2007). Currently 90% of all the water used in the Las Vegas Valley is pumped from Lake Mead. With the extension of drought in the Rocky Mountains, and a continued decrease in flow, it is unlikely that Nevada will be granted an increased allocation of water from the Colorado River. Therefore, water managers in Las Vegas have sought to explore alternatives to providing fresh water to the region. In addition to water saving practices that were mentioned above, the Southern Nevada Water Authority has begun

exploring water resources located in Spring Valley and Snake Valley, NV. Each of these valleys is approximately 400,000 hectares in size and could provide the opportunity for water to be piped to Las Vegas. Studies of these basins suggest that they are at least partially hydrologically closed and are fed mainly from mountain snow melt. Ground water in Spring Valley is typically within 4 m from the surface, while in Snake Valley it can be reached within 9 m (Devitt et al., 2008). A series of ecological studies has been conducted since 2004 using various techniques such as Eddy Covariance (EC) and remote sensing to estimate available water in the basins (Devitt et al., 2009). In particular, EC stations measured evapotranspiration (ET) in the phreatophytic zones of these basins, which are comprised of mixed shrubland species. One of the dominant species at many locations is greasewood (*Sarcobatus vermiculatus*), a deep rooted long lived woody shrub. Greasewood is a facultative phreatophyte with the ability to access both unsaturated and saturated soil zones (Trent et al., 1997; Cooper et al., 2006). Therefore, the water use characteristics of this species were investigated more closely during the process of closing water balances in each valley (equation 1).

$$ET = I - O - \Delta S \quad \text{Equation (1)}$$

Where, I is the input (from precipitation and snow melt runoff), O is the output (drainage and runoff), and ΔS is the change in water storage. Because the basins are thought to be mostly closed, ET is believed to account for the majority of basin discharge (Devitt et al., 2008).

In addition to EC and remote sensing techniques, a research project was initiated during the growing season (April-September) of 2007 to assess water use (sap flow) of *S. vermiculatus* under various treatments. The goals of this project were to investigate the water use of *S. vermiculatus* under conditions which may be experienced during a water table drawdown. Treatments included: 1) severing the tap root of the shrub (ST group) such that ground water accessibility would no longer be possible; 2) preventing (minimizing) infiltration of precipitation around the shrub (IP group), which should cause the shrub to shift towards a ground water acquisition regime; and 3) a control (TC) which would have access to water in both the unsaturated vadose zone and the phreatic zone.

It was hypothesized that ST treatments might experience greater stress than the IP or TC groups as the growing season progressed and as soil moisture became depleted. Furthermore, it was hypothesized that IP groups might experience higher sap flow than ST groups throughout the growing season, but would be lower than the TC sap during periods of the growing season that experienced precipitation because the TC group would have access to an additional water source. During dry periods it was expected that sap flow in the IP and TC groups would be similar. Finally, it was hypothesized that flow rates in the TC and IP groups at site SV 1 would be higher during the spring and early summer, compared to the treatments at site Snk 2, because depth to groundwater at site SV 1 was shallower. However, as the growing season progressed, plants at site Snk 2 would shift to obtaining groundwater, in addition to vadose zone water, which would allow them to have similar sap flows to treatments located at SV 1.

Methods

Site Description

During the spring/summer of 2007, a series of sap flow systems were installed in Spring Valley and Snake Valley, Nevada on the phreatophytic shrub *Sarcobatus vermiculatus*. The valleys are located in the Great Basin Desert, which is about 306,000 square kilometers and is considered to be the largest US desert. The Great Basin Desert is bordered by the Sierra Nevada Range to the west and the Wasatch Range to the east. This cold desert has an annual rainfall of 200-350 mm, most of which occurs as winter snowfall. Average daytime high temperatures during the summer months are approximately 32°C (Weisberg et al., 2007). Vegetation in the basin is typically low and homogeneous, with four major shrubs occurring at the study sites: *Atriplex confertifolia* (shadscale), *Artemisia tridentata* (big sagebrush), *Sarcobatus vermiculatus* (greasewood), and *Chrysothamnus nauseosus* (rabbitbrush).

Two separate sap flow systems (Flow32, Dynamax, Houston TX, USA) were installed at established research sites named Spring Valley 1 (SV1) and Snake Valley 2 (Snk2). SV1 is located at 38.776N, -114.186W. Percent cover of *S. vermiculatus* at this site was approximately 3% and soil texture at the surface was classified as sandy loam. Snk2 is located at 39.038N, -114.058 W. Percent cover of *S. vermiculatus* at this site was approximately 13% and soil texture at the surface was classified as a clay loam.

Treatments

Three different treatment groups and one control group were created at the SV1 and Snk2 sites. The first treatment group (tagged ST) was established using a large tree spade to sever the tap root of four separate *S. vermiculatus* shrubs. The spade was

inserted into the soil (~1.2 m) around the shrub and lifted until visual confirmation was made that the root had been severed (Fig. 3-1A). The second treatment group (tagged IP) was established by laying a heavy plastic sheet around the plant to prevent/minimize vertical infiltration (Fig. 3-1B). The plastic was placed beyond horizontal root extension (75% of distance between neighboring plants) and was covered with 5 cm of nearby surface soil. The final treatment group (tagged SC) was established by placing the tree spade in the soil around the shrub to disturb shallow roots, while leaving the tap root intact. This treatment group did not include sap flow gauges, but was monitored using a number of instruments (described below) which assessed the plants physiological water status.

Instrumentation

Four *S. vermiculatus* shrubs in the TC, IP, and ST groups were each fitted with 8-10 mm stem flow gages (Dynamax, Houston TX, USA) at the SV 1 and Snk 2 sites. Stem diameters were measured using digital calipers and then lightly sanded, cleaned, and sprayed with Canola release spray. Gages were secured with Velcro and a G4 compound was placed above and below the sensors to seal out moisture, prevent sensor corrosion, and allow for expansion/contraction of the heater and gage. An upper and lower o-ring was then fitted to the stem and a weather shield was secured using electrical tape, to prevent water from reaching the sensors and radiation from affecting readings. Finally, in cases where the sensor was located near ground surface, aluminum foil was wrapped along the stem from the ground to the gage, to prevent soil temperatures from upsetting the equalization of the stem to the ambient temperature. Devitt (1993) showed that this technique was effective and that errors were small during periods of high temperatures

when run periods averaged greater than 2-3 days (experiments here all lasted longer than three days).

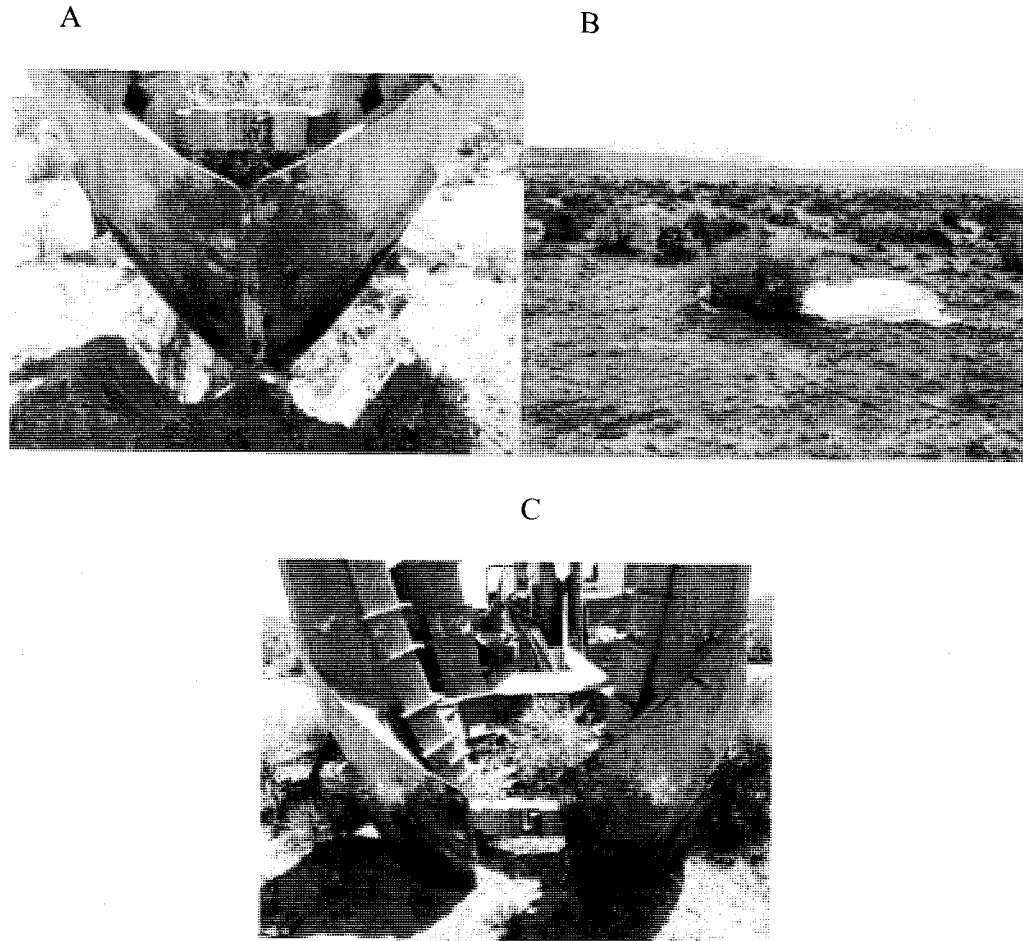


Figure 3-1. Photos documenting experimental set up of treatment groups: (A) Severed Tap group (ST), (B) Infiltration Prevention/minimization (IP), and (C) Severed Control (SC).

Gages were then connected to extension cables that ranged from 8-15 m in length. Data loggers (CR10X, Campbell Scientific, Logan UT, USA) were used with the Flow32 program. Each data logger had an eight-gage capacity and therefore SV1 and Snk2 sites each contained two data loggers to allow for the monitoring of twelve gages at each site.

Site visits occurred every three-four weeks and data were downloaded to a laptop PC.

The data file was later converted to an excel file and entered into an excel macro model provided by Dynamax.

In addition to the stem flow system, a weather station (Campbell Scientific, Logan UT, USA) was installed at SV 1 and Snk 2. The weather station was fitted with a tipping bucket rain gage, solar pyranometer, anemometer, weather vane, barometric pressure sensor and a temperature/relative humidity probe. Data were collected continuously but only 30-minute averages were recorded on the CR10X data logger. Hourly data were incorporated into the Penman-Monteith equation to predict reference evapotranspiration ($ET_{ref} - grass$)

Soil, environmental, and plant physiological measurements

Environmental demand and plant water status of each *S. vermiculatus* shrub from the SC group and those fitted with stem flow gages from the TC, IP, and ST treatments were assessed during each site visit. Plant measurements occurred during midday and included: leaf xylem water potential (Scholander Pressure Bomb, PMS Instruments, Corvallis OR, USA), chlorophyll index (CM-1000, Field Scout, Plainfield IL, USA), and canopy temperature (Infrared Thermometer, Cole Parmer Instruments, Vernon Hills, IL, USA). Soil measurements included surface temperatures (Infrared Thermometer, Cole Parmer Instruments, Vernon Hills, IL, USA), and volumetric soil water content at 5-cm depth (HH2 Moisture Meter, Delta-T Devices, Burwell Cambridge, UK).

Stable Isotope Deuterium

The stable isotope deuterium was used to determine the response of *S. vermiculatus* to episodic summer rainfall events. Stem cuttings and transpirational

capture were taken from each treatment, along with soil samples, groundwater and rainwater (Spring Valley only) in each valley in the beginning of June and the end of July to determine deuterium fractionation. Transpirational capture was accomplished by placing plastic bags over transpiring leaves of each treatment until at least 1-ml of water was obtained (typically ~15 minutes). The captured water was then placed in scintillation vials and stored on ice. Additionally, stem cuttings were taken from each treatment (later used for stem exudation) and also placed in vials and stored on ice. A rainwater sample was obtained from Spring Valley and stored on ice (Snake Valley did not have any samples available). Finally, soil samples were obtained at 15 cm in addition to samples with depth using an auger down to 1.5 m and placed on ice. In the lab, the soil samples were placed in a closed flask system which was submerged in high temperature oil. A vacuum system was used to pull vapor from the flask over dry ice to cryogenically trap the vapor as water. All samples were placed in vials and immediately frozen. Samples were sent to the University of Utah for analysis of deuterium.

Analysis of Stem Heat Balance

The Flow32 sap flow monitoring system consists of a series of stem flow gages and CR10x data loggers. Data were collected every 30 minutes from dawn until dusk. Gages used multiple pairs of differentially wired thermocouples, which were averaged together electronically. The sap flow and sap heat flux were assessed using an energy balance approach. This required a steady input of energy (Q_h) from the heater strip located inside each gage, which was equivalent to the power input from the heater (P_{in}). The heater surrounds the stem and was powered by a DC supply located inside the data logger storage compartment. This DC supply is charged via two solar panels mounted on

vertical galvanized poles. Radial heat (Q_r) was conducted through the gage to the ambient side. Vertical heat (Q_v) is broken down into upward (Q_u) and downward (Q_d) heat conduction. The remainder of P_{in} , Q_u , Q_d , and Q_r gives the heat convection carried by the sap (Q_f). Once Q_f was found, it was divided by the specific heat of water and sap temperature increase yielding mass flow rate. This is expressed mathematically by the Dynamax manual (2005) as:

$$\begin{aligned} P_{in} &= Q_r + Q_u + Q_d + Q_f (W) \\ P_{in} &= V_2 / R \end{aligned} \quad \text{Equation (1)}$$

$$\begin{aligned} Q_v &= Q_u + Q_d \\ Q_u &= K_{st} * A * dTu / dx \\ Q_d &= K_{st} * A * dTd / dx \end{aligned} \quad \text{Equation (2)}$$

Where K_{st} is the thermal conductivity of the stem (W/m^*K); A is the stem cross-sectional area (m^2); dTu/dx and dTd/dx are the temperature gradients (K/m); and dx is the spacing between thermocouple junctions. These thermocouple junctions were located above and below the heater and both measured a rise in sap temperature. Channel AH measured $A-Ha$ (mV), and channel BH measured $B-Hb$ (mV). The difference between these two signals was equal to the axial heat conduction (Q_u and Q_d) (Dynamax, 2005):

$$BH - AH = (B - Hb) - (A - Ha) = (B - A) + (Ha - Hb) \quad \text{Equation (3)}$$

Additionally, the distances between the upper and lower thermocouples were fixed such that the components of Q_v could be combined with a common denominator:

$$Q_v = Kst * A * (BH - AH) / dx * .040 \text{ (mV/C)} \quad \text{Equation (4)}$$

Once Q_f was solved, the flow rate per unit of time was calculated from the residual of the energy balance in Watts, and divided by the temperature increase of the sap and the heat capacity of water (Dynamax, 2005). This is expressed by:

$$F = (Pin - Q_v - Q_r) / Cp * dT \text{ (g / s)} \quad \text{Equation (5)}$$

where $Q_r = Ksh * CH$ and Ksh is the thermal conductance constant of a particular gage, and CH is the channel which measures radial heat loss. Taking the average of the apparent Ksh between 2-4 am, when near zero flow is observed, gave the minimum Ksh because radial heat loss is at its maximum and convective heat loss is at its minimum. This apparent Ksh was calculated for each gage and used throughout the project, such that systems were able to be shut down at night to prevent stem overheating. In equation 5, C_p is the specific heat of water (4.186 J/g°C) and dT is the temperature increase in sap measured by the average of the AH and BH signals which are then converted to degrees C by dividing by the thermocouple constant (Dynamax, 2005):

$$dT = \frac{(AH + BH) / 2 \text{ (mV)}}{.040 \text{ (mV / C)}} \quad \text{Equation (6)}$$

Data-Post Processing

Channel voltages and stem parameters were downloaded from the CR10x and a flow rate was calculated in EXCEL using a Dynamax model. Following the final download, whole plant and subsamples (which were fitted with the stemflow gages), were all harvested, dried, and weighed. A leaf area camera was used to estimate leaf area in cm^2 on the subsamples and whole plants harvested from each treatment. During the experiment, many subsamples experienced severe canopy die back from the heating element on the stemflow gages. When observed gages on plants with severe dieback were changed to different branches and new diameters were entered into the Flow32 program. Pictures were taken of each subsample during the site visits to aid in scaling flow from the subsample to the entire canopy on treatments which had experienced die back earlier in the measurement period.

For subsamples that did not experience die-back during the entire monitoring period, their flow rates were normalized based on dry leaf area. These rates were then scaled to the entire shrub, based on the entire shrub leaf area. For plants that had dieback on subsamples, photos were evaluated using Photoshop software (Photoshop CS2, Adobe Systems Inc, San Jose CA, USA). The count of pixels within each photo that contained leaves was quantified. Pixels were also calculated for subsamples with known leaf weights, establishing a pixel/weight relationship. Correlations of pixels and weight for TC and IP at site SV 1 had an r^2 of 0.78 and ST had an r^2 of 0.99, while at site Snk 2 TC and IP had an r^2 of 0.88, all significant at $P < 0.05$. Additionally, harvested subsamples were used to create a leaf area/weight relationship. At site SV 1, the relationship for TC and IP had an r^2 of 0.93, at ST the relationship had an r^2 of 0.99, while at site Snk 2 TC

and IP had an r^2 of 0.98, all significant at $P < 0.05$. With these established correlations, pixel leaf area for plants prior to die back were used to predict the weight of those subsamples, which were then inserted into the weight/leaf area equation to predict subsample leaf area of the stems that had died. TC and IP subsamples were combined to increase the robustness of the correlation. However, ST subsamples had drastically different leaf morphology and therefore had independent correlations calculated. Flows occurring prior to dieback were then normalized using these predicted leaf areas. Finally, flow was scaled to the entire leaf area of the plant based on whole plant dry leaf weights, which was obtained by harvesting the above ground plants in each treatment at the end of the experimental period.

Data Analysis

Two-way ANOVAs were used to assess the differences in plant physiological measurements and soil measurements between treatments and site visits. Furthermore a series of t-tests were used to assess differences between TC and IP treatments located at sites SV 1 and Snk 2. Data from treatment ST were not included in this analysis because shrubs from site Snk 2 had a 100% mortality rate. For sap flow rate comparisons, a two-way ANOVA could not be used because data failed the normality and equal variance assumptions of the statistical test. Transformations of the data also failed to make the data pass the requirement of the parametric test. Furthermore, because there is no nonparametric equivalent to a two-way ANOVA, the Kruskal-Wallis one-way ANOVA was used to calculate first treatment differences at sites SV 1 and Snk 2, and then temporal differences. Finally, valley treatments were compared using either a t-test (when

normality in the data existed) or a Mann-Whitney test (when the normality assumption could not be fulfilled).

Results

The precipitation and potential ET (ET_{ref}) for the growing season (May-October) are shown for both SV 1 (A) and Snk 2 (B) in Figure 3-2. Total precipitation at SV 1 was 34.5 mm, while precipitation at Snk 2 it was 11.9 mm. Rainfall amounts at SV 1 and Snk 2 were compared from 6/1/2007-9/6/2007, when stations at both sites became operational. Additionally, SV 1 received one large rainfall event on 8/1/2007 of 19 mm that Snk 2 did not receive, resulting in a larger total at that site. A t-test revealed that daily ET_{ref} at Snk 2 was significantly higher than SV 1 (mean of 6.74 mm and 7.25 mm respectively, $P = 0.032$), indicating that plants at Snk2 experienced higher environmental demand.

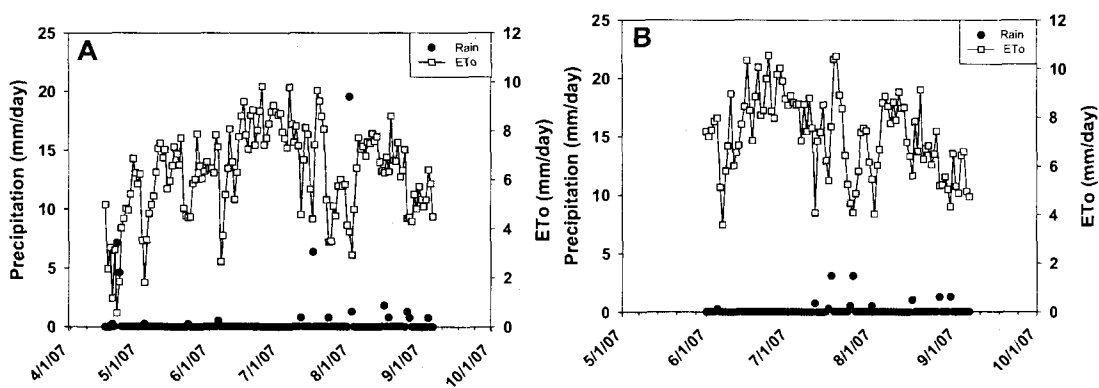


Figure 3-2. Precipitation and potential ET (ET_o) for SV 1 (A) and Snk 2 (B) during the growing season of 2007.

Both valleys experienced a dry spring and early summer period, while daily ET_{ref} was higher than average. By late July, summer precipitation events became more frequent (nine events at SV 1, eight at Snk 2) and ET_{ref} declined. However, ET_{ref} did increase after the rainy period from 4-6 mm/day to about 6-8 mm/day from the middle of August until the middle of September.

Plant Physiological Measurements

A series of physiological measurements were taken on plants of each treatment as shown in Figures 3-3 (SV 1) and 3-4 (Snk 2). Plant tissue moisture content at SV 1 was maintained at 75-80% for each treatment with the exception of ST (Figure 3-3 A) which experienced a significant ($P < 0.001$) decline in tissue moisture content by July 19, 2007 (from 0.70 to 0.50), but demonstrated a recovery by August 16, 2007.

The chlorophyll index is shown in Figure 3-3 B. A two-way ANOVA showed that on 6/21/2007 and 7/19/2007, ST was significantly lower ($P = < 0.001$) than TC, SC, and IP, with no significant differences between all other treatments. However, it should be noted that the chlorophyll index values were area integrated such that shrubs with sparse canopy development were more problematic. However, on 8/16/2007, SC had significantly higher ($P < 0.001$) tissue moisture content when compared to IP and ST ($P < 0.05$), but no other significant differences were noted between treatments. Furthermore, the chlorophyll index declined significantly ($P < 0.05$) in the TC and SC treatments for each sampling period, which may reflect increased stress and the early stages of leaf senescence. The ST treatment showed no significant change until the last sampling period, where an increase compared to 6/21/2007 ($P < 0.05$) was observed.

Finally, IP showed no significant change in the chlorophyll index across each sampling date.

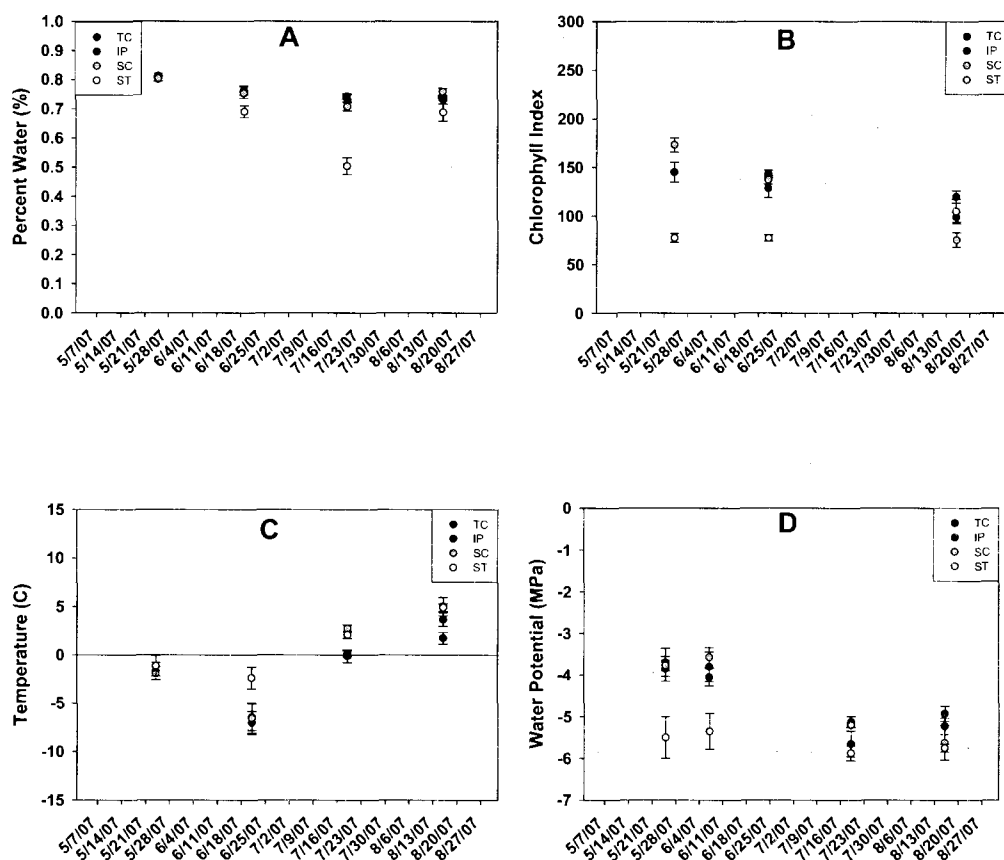


Figure 3-3. SV 1 plant measurements taken during site visits to assess plant water stress: A) leaf tissue moisture, B) chlorophyll index, C) canopy-air temperature differentials, and D) leaf-xylem water potential. Treatment abbreviations: True Control (TC), Infiltration Prevention (IP), Severed Control (SC) and Severed Tap (ST).

Canopy-air temperature differentials are shown in Figure 3-3 C. The ST treatment had a significantly higher ($P < 0.05$) $T_c - T_a$ than TC, IP, and SC only on 6/21/2007. For all other measurement periods, no significant differences were observed in $T_c - T_c$ across all

treatments. However, it should be noted that the infrared thermometer temperatures were area integrated such that shrubs with sparse canopy development were more problematic. All treatment groups showed a significant ($P < 0.05$) decrease in $T_c - T_a$ from May-June, and a significant increase in $T_c - T_a$ from June-July. From July-August, only IP showed a significant increase ($P < 0.05$) in $T_c - T_a$, while all other treatments had no significant differences.

Finally, leaf xylem water potentials (ψ_L) are shown in Figure 3-3 D. ψ_L from ST treatments were significantly ($P < 0.05$) lower than all other treatments for the May and June measurement periods, while TC, IP, and SC water potentials were not significantly different. No significant differences were observed between treatments in July and August. Furthermore, ST showed no significant temporal change in ψ_L , while TC, IP, and SC all showed a significant ($P < 0.05$) decrease from June to July. No significant change in ψ_L was observed for TC, IP and SC from May to June and from July to August.

Leaf tissue moisture content for treatments at Snk 2 for the 2007 growing period are reported in Figure 3-4 A. No significant differences in tissue moisture content between and within treatments were observed for the four sample periods. Chlorophyll index for Snk 2 is reported in Figure 3-4 B. The SC treatment had a significantly lower chlorophyll index than the IP and TC groups in June and July, no significant difference was observed between chlorophyll index in May and August. Data from IP and TC did not differ significantly amongst all measurement periods. Additionally, SC did not show any significant differences in chlorophyll index over time, while IP and TC showed a significant decrease in chlorophyll index from the July to August measurement periods.

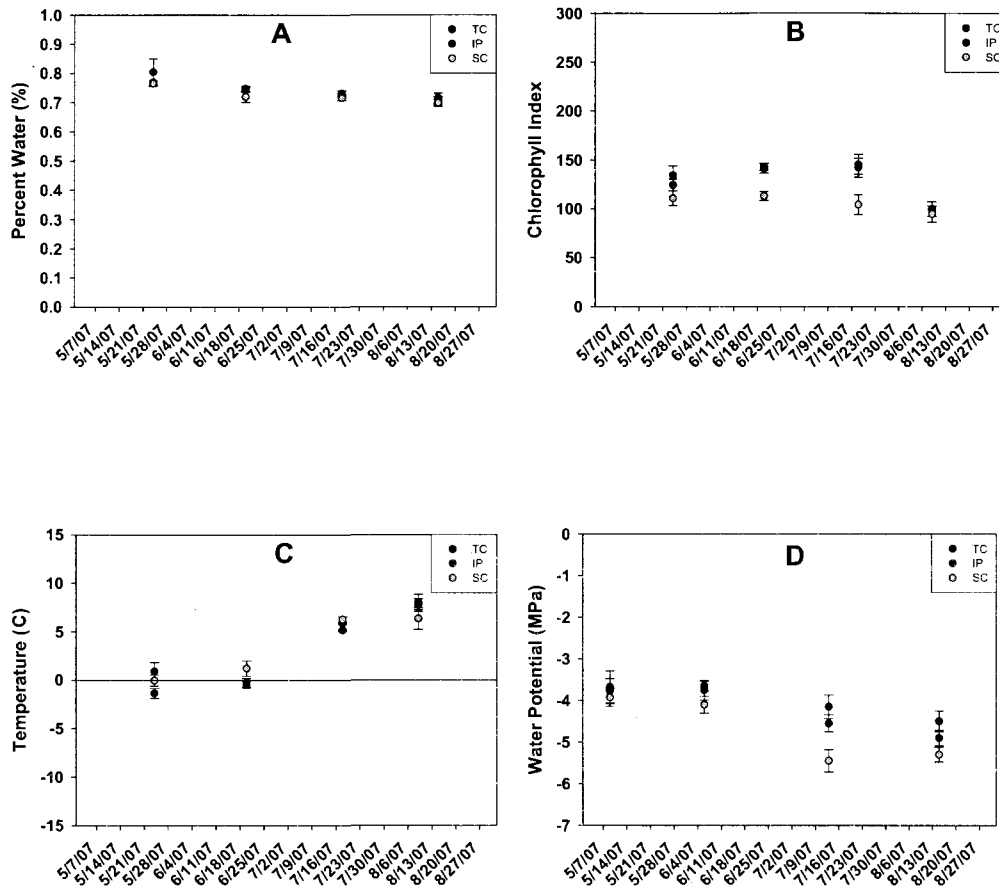


Figure 3-4. Snk 2 plant measurements taken during site visits to assess plant water stress: A) leaf tissue moisture, B) chlorophyll index, C) canopy-air temperature differentials, and D) leaf-xylem water potential. Treatment abbreviations: True Control (TC), Infiltration Prevention (IP), and Severed Control (SC).

Canopy-air temperature differentials for the Snk 2 treatment groups are reported in Figure 3-4 C. TC had a significantly lower ($P < 0.05$) $T_c - T_a$ value when compared to IP in May, but no other significant differences were observed between treatment groups for all other measurement periods. A significant increase ($P < 0.05$) in $T_c - T_a$ was observed within all treatment groups when comparing June and July, and July and August, but no significant difference were observed between May and June.

Finally, ψ_L is shown in Figure 3-4 D. Data from SC was significantly lower ($P<0.05$) than IP and TC in July, but there were no significant differences between treatments for all other measurement periods. Furthermore, IP showed no significant temporal differences in ψ_L , while TC showed a significant decline in water potential ($P<0.05$) when August values were compared to May and June values. Data from SC also showed a significant decline ($P<0.05$) in ψ_L when August and July values were compared to May and June values. No significant difference in ψ_L for both TC and SC were observed between May and June.

Differences associated with the ST group, when compared to TC and IP, were due to the tap root being severed rather than simply a disturbance occurring from the tree spade (plants in SC had the spade inserted, but the tap root was not severed), as the SC group did not reveal significant differences with the TC and IP treatments.

Spring Valley and Snake Valley Comparisons

A series of t-tests were used to assess differences between the TC and IP treatments at SV 1 and Snk 2 sites (plants used in ST treatments had all died at the Snk 2 site, and plants used in SC treatments did not have sap flow gages on them). Between valleys, tissue moisture was significantly higher ($P<0.05$) in May at SV 1 for the IP group. All other tissue moisture values were not significantly different. The TC treatment also showed a significantly higher chlorophyll index ($P<0.05$) at SV 1 for the June measurement period, while all other values were not significantly different. Canopy-air temperature differentials for TC and IP between valleys were not significantly different for the May measurement period, but the temperature differentials were significantly higher ($P<0.05$) at Snk 2 for both IP and TC for all other measurement periods. Finally

ψ_L was significantly lower ($P < 0.05$) at SV 1 for both IP and TC in July when compared to Snk 2. There were no significant differences for the other measurement periods.

Leaf Sodium Content

Greasewood is a known halophyte that has been found along extreme salinity gradients (Donovan et al., 1997). Leaf Na was determined for treatment groups at SV 1 and Snk 2 to demonstrate that some vadose zone root water uptake must take place to support the Na demands of the plant. These ions are especially important to halophytes as they are needed for osmoregulation (Patel and Pandey, 2007). Results are shown in Figure 3-5.

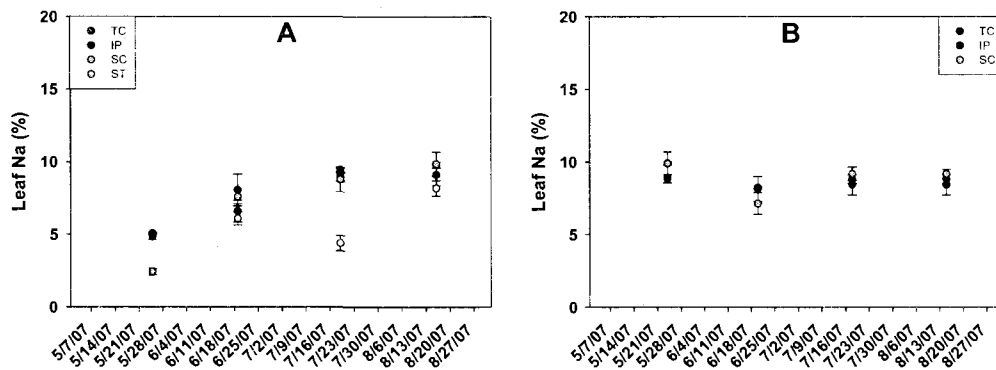


Figure 3-5. Leaf Na content for SV 1 (A) and Snk 2 (B) treatment groups. Treatment abbreviations: True Control (TC), Infiltration Prevention (IP), and Severed Control (SC).

Figure 3-5 A shows the leaf Na content for all treatment groups at SV 1. Data from SC showed significantly ($P < 0.05$) lower leaf Na content when compared to TC and IP during the May measurement period, while TC and IP did not differ significantly. The ST treatment also had significantly ($P < 0.05$) lower Na tissue concentrations when

compared to all other treatments during the July measurement period. No significant differences were observed between treatments during the June or August measurement periods. Furthermore, TC did not show a difference in Na tissue concentration over time, while IP was significantly higher ($P < 0.05$) in July and August when compared to June and SC was significantly ($P < 0.05$) higher in August when compared to June. Finally, data from ST showed a significant ($P < 0.05$) increase in Na tissue concentration only when comparing August to July. These differences may be a reflection of a concentration effect associated with leaf biomass, as ST treatments had smaller leaves. Additionally, nutrient acquisition may have been easier under the TC treatments due to early spring rainfall that would have been minimized in the IP plants.

Snk 2 leaf Na concentration is shown in Figure 3-5 B. No significant differences were observed between groups for all measurement periods, which was not surprising as *S. vermiculatus* is a leaf succulent, sodium-accumulating shrub (Khan et al., 2002). Furthermore, only data from SC showed a significant decline in leaf Na concentration from May-June, while all other treatments showed no significant changes in leaf Na with time. The existence of similar leaf Na concentrations across all treatments may be a reflection of a deeper vadose zone combined with a clay soil texture to allow for enhanced nutrient acquisition when compared to SV 1.

Comparisons of data from TC and IP between valleys for the four measurement dates revealed only a significant difference ($P < 0.001$) in leaf Na concentration for May. During this time period Snk 2 treatments had higher leaf Na than SV 1 treatments. No significant differences in leaf Na content between valleys were observed for all other measurement dates.

Soil Measurements

To assess available soil moisture in the near surface region (responsive to rainfall events), soil volumetric water content was assessed at a depth of 15 cm underneath the plant canopies of TC and IP treatments using time domain reflectometry (TDR). Data from these measurements are shown in Figure 3-6.

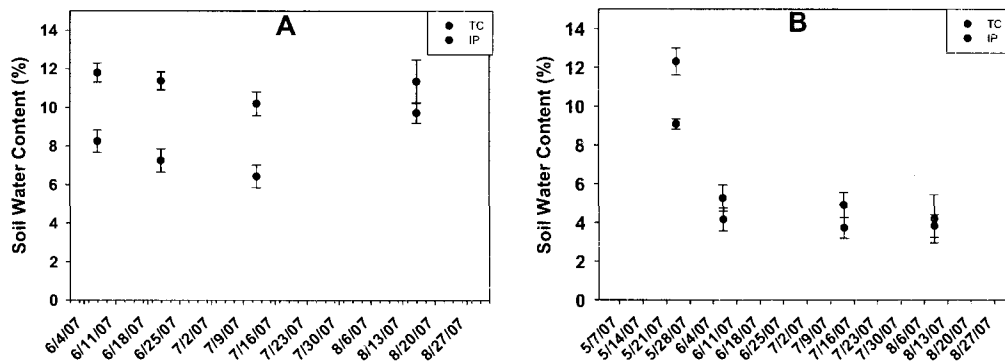


Figure 3-6. Soil water content at each treatment shrub located at SV 1 (A) and Snk 2 (B) sites. Treatment abbreviations: True Control (TC), and Infiltration Prevention (IP).

In Figure 3-6 A) soil water contents at site SV 1 were significantly ($P < 0.05$) higher in the IP soils when compared to the TC soils for all dates except the August measurement period. These data suggest that the plastic was not only minimizing infiltration but was also preventing evaporation from the soil. Additionally, IP did not differ significantly over time, while water content at TC was significantly higher in August when compared to all other measurement periods, which may reflect the 19 mm of rain that occurred in early August. Results from site Snk 2 (Fig 3-6 D) are similar to site SV 1. Soil water content in the IP treatment was significantly ($P < 0.05$) higher than

the TC treatment only during the May measurement period. Additionally, both TC and IP had significantly ($P < 0.05$) higher water contents in May when compared to all other periods. These data suggest that residual soil moisture in the in the near surface soil was quickly transpired or evaporated early in the spring. Furthermore, it is unknown why rainfall events did not increase soil moisture at 15 cm later in the growing season. However, this may have been a direct reflection of greater soil evaporation and/or plant water uptake.

Figure 3-7 shows salinity and Na concentrations in soil samples that were collected during the 2004 and 2007 well installations. The salinity data for both SV 1 and Snk 2 (Figure 3-7 A and B) reveals a high concentration of salts in the upper 4.6 m of the soil profile. Additionally, the Na concentration was also highest in the upper 4.6 m (Figure 3-7 C and D) for both valleys, decreasing to very low values below this depth. Comparisons between the two valleys revealed much higher soil salinity and Na concentrations at the Snk 2 site when compared to the SV 1 site. Differences between the two sites were most likely due to differences in the soil types (SV 1 is a sandy soil and Snk 2 is a clay loam). At SV 1 sand accounted for 85% of the texture in the upper 28 cm while at Snk 2 clay and silt account for 73%. The importance of this figure, however, is that the upper 4.6 m of the soil profile reflects a concentration effect most likely linked to an active region of root water uptake associated with deep rooted shrubs such as *S. vermiculatus*.

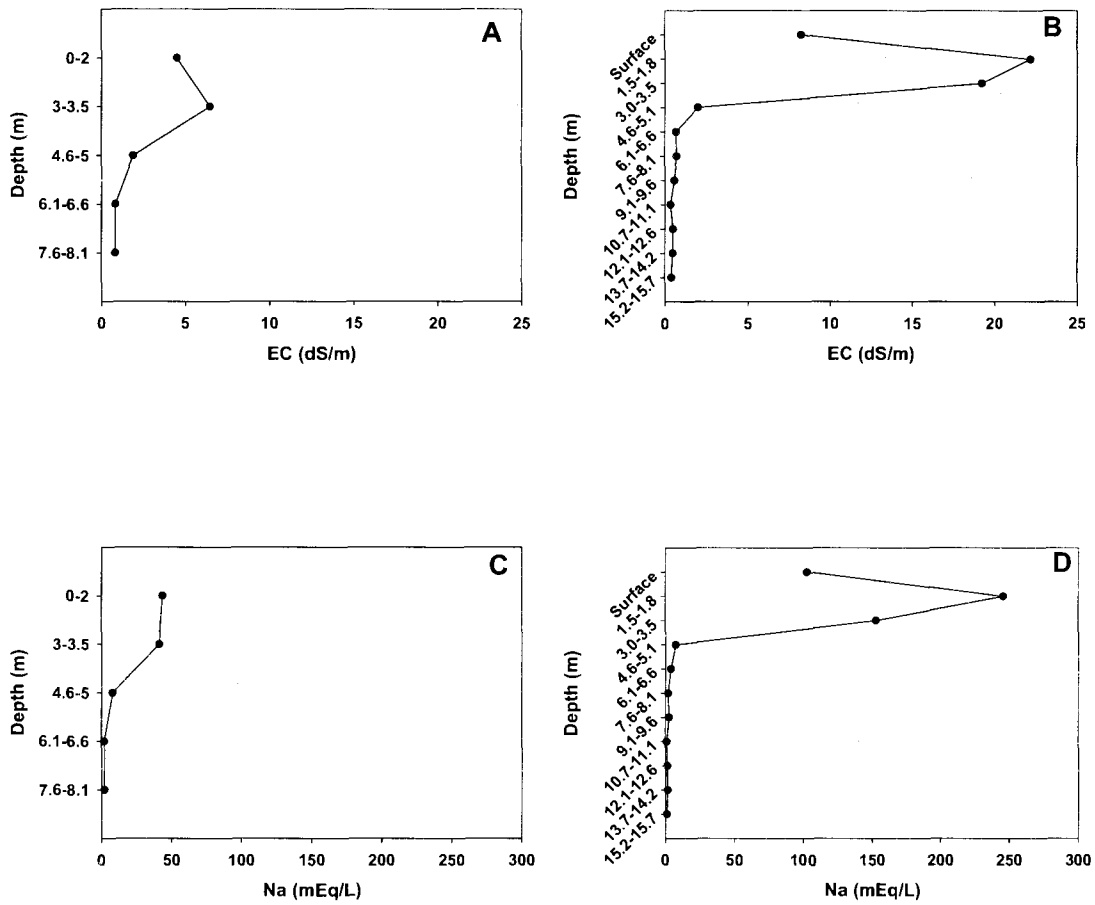


Figure 3-7. Salinity and Na concentrations with depth at SV 1 (A and C) and Snk 2 (B and D) taken during well installations in 2004 and 2007.

Isotopic Analysis

To assess water sources used by plants, isotopic analysis of *S. vermiculatus* was investigated during June and August. These results are shown in Figure 3-8 A and B for both valleys. Differences in deuterium levels between groundwater and vadose zone water occur when soil water evaporation enriches deuterium (Barnes and Allison, 1988). At SV 1 and Snk 2, stem exudation was used to evaluate deuterium signatures as influenced by the treatments imposed. For SV 1 TC, IP and ST were included in the

analysis while at Snk 2 only TC treatments were available. Additionally, soil water extraction and rainwater (only at SV 1) were included for comparison. Figure 3-9 A demonstrates that both June and August deuterium levels from the TC and ST treatment were closest to rainwater and soil moisture from 0-15 cm depth. This suggests that some vadose zone water extraction was occurring in this valley during these collection periods, which both occurred following rainfall events during the summer period.

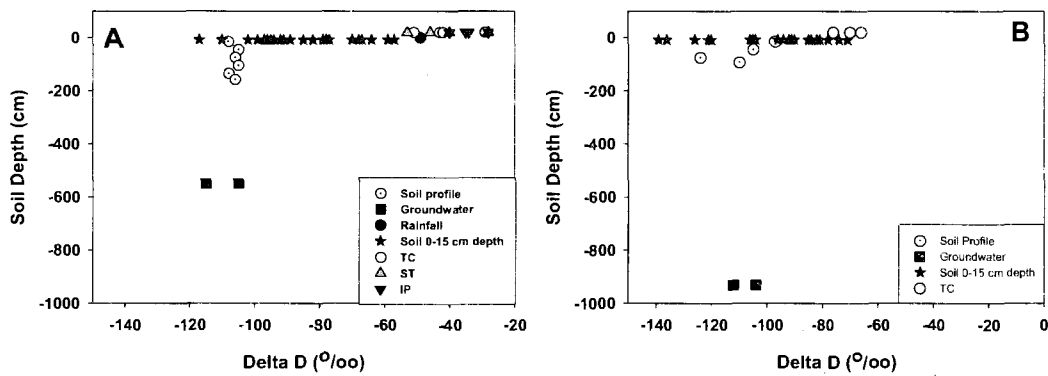


Figure 3-8. Isotopic analysis of ground water, soil water, and stem exudation at SV 1 for TC and ST treatments (A) and Snk 2 for the TC treatment (B).

The groundwater samples shown in Figure 3-8 reveal lower levels of delta D than the majority of vadose zone samples, suggesting that the vadose samples are enriched because of evaporation and that the source of groundwater may be from snowmelt mountain recharge. Lee et al. (2007) explained that generally, the stable isotopic composition of precipitation decreases with decreasing temperature; thus, recharge associated with winter precipitation would have lower deuterium levels. However, this is not to say that greasewood plants at these sites were not utilizing groundwater, as only

two samples during the entire growing season were collected and both were during the summer period. The results do suggest that greasewood does respond to episodic summer rainfall events, as the TC and ST treatments at SV 1 and TC treatment at Snk 2 appear to be more closely linked to rainwater deuterium levels.

Ground Water Data

A pressure transducer was installed in each well to record water table elevation throughout the growing season. Figure 3-9 shows depth to groundwater for both SV 1 and Snk 2. Inset graphs show groundwater fluctuations from 7/1/07-7/16/07.

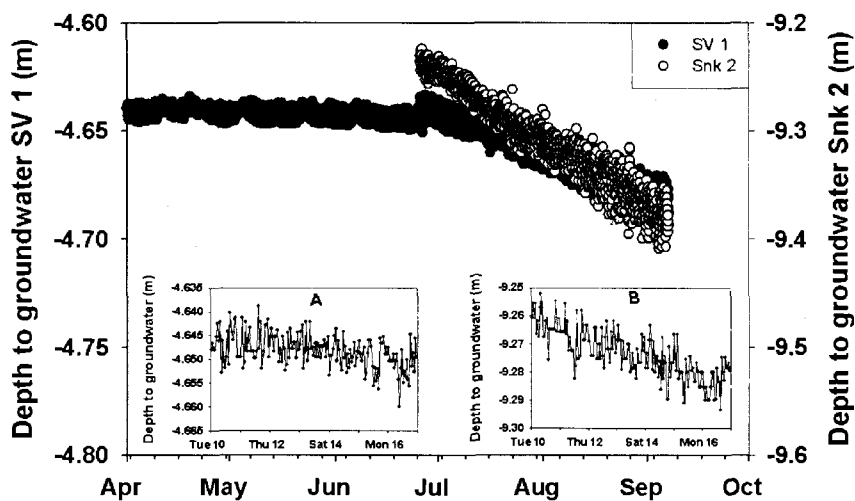


Figure 3-9. Depth to groundwater for SV 1 and Snk 2. Depth to groundwater at Snk 2 was 9.31 m and at SV 1 4.66 m. Inset A are groundwater fluctuations at SV 1 from 7/1/07-7/16/07. Inset B are groundwater fluctuations at Snk 2 from 7/1/07-7/16/07.

Data for Snk 2 coincides with well installation and therefore spring hydrograph data was not available. At SV1 (complete data set) the depth to water began to decline in July with amplified fluctuations toward the end of summer. These fluctuations may be a combined

effect of both increased root water uptake from groundwater and a decrease in recharge. Furthermore, the decline in the water table associated with increased fluctuations, were more pronounced at Snk 2 (Fig. 3-9 insets A and B), which may be due to a dependence on sediment texture. Loheide et al. (2005) showed that finer-grained materials (such as clay-rich soils) produce larger water table fluctuations and slower recovery rates when compared to coarser material (such as sand). Soil at SV 1 contained greater than 85% sand from ground surface to the water table, while Snk 2 had a 50%-75% silt/clay mixture throughout the vadose zone. Diurnal fluctuations in the water table in conjunction with a seasonal decline in depth to water, suggest that some fraction of root water uptake was from groundwater in both valleys.

Sap Flow

Sap flow was calculated by downloading the Flow32 data and entering the stem parameters and channel voltages for each treatment into a Dynamax EXCEL model. This sap flow was then normalized on a leaf area basis, and scaled from subsample to entire shrub on a daily flow basis. Results of normalized shrub based sap flow are shown in Figure 3-10 for both SV 1 and Snk 2. SV 1 consisted of all three treatments groups throughout the growing season. Flow rate (g/day/cm^2) was calculated on a shrub basis and is shown in Figure 3-10 A. A Kruskal-Wallis one way ANOVA showed that TC had significantly ($P<0.05$) higher sap flow than ST for all measurement periods except during August. Furthermore, TC had higher sap flow ($P<0.05$) than IP in May, but differences between the two treatments were not-significant for the remainder of the growing season. Data from IP also showed significantly ($P<0.05$) higher sap flow than ST in May, June, and July, while in August there was no significant difference between the two treatments.

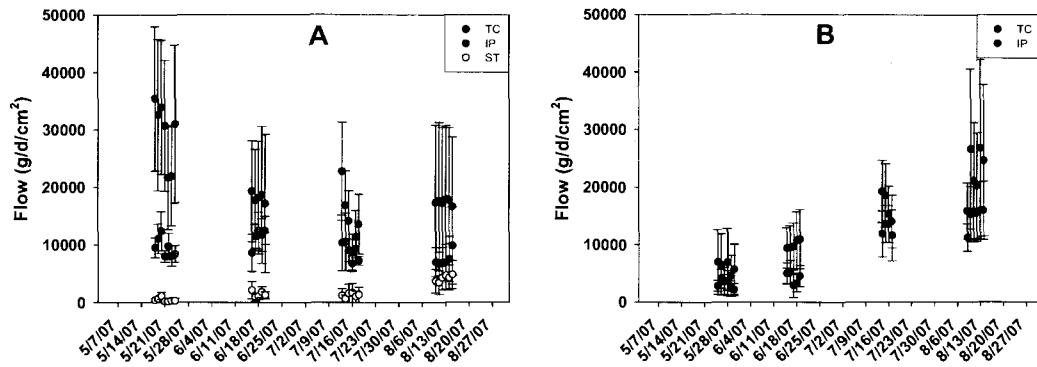


Figure 3-10. Normalized scaled shrub sap flow for SV 1 and Snk 2. Treatment abbreviations: True Control (TC), Infiltration Prevention (IP), and Severed Tap (ST).

The ANOVA also showed a significant ($P < 0.05$) decline in sap flow in the TC treatment when May was compared to June, July and August. There were no significant differences in flow between the other measurement periods. Data from IP also did not show any temporal effect on sap flow at SV 1, while ST showed an increase in sap flow throughout the growing season. ANOVA indicated a significant increase in ST sap flow for all measurement periods except when June was compared to July.

Figure 3-10 B is the shrub sap flow for Snk 2. A Kruskal-Wallis one-way ANOVA revealed that TC had significantly ($P < 0.001$) higher flow rates than IP only in June, while there was no significant difference between treatments for the remainder of the measurement periods. Furthermore, TC had a significantly ($P < 0.05$) higher flow rate in August when compared to May and June, but no significant differences existed between August and July, and May and June. Data from IP showed significantly ($P < 0.05$) higher flow in August and July when compared to May and June, but there was no significant difference between July and August, and May and June.

Statistical comparisons were also made between valleys based on treatments. The nonparametric Mann-Whitney test was used in comparisons where non-normality existed, and the t-test was used when normality was present. The TC treatment at SV 1 had significantly ($P=0.002$) higher flow than the Snk 2 TC treatment in May, but was not significantly different for all other measurement periods. Data from IP at SV 1 showed significantly higher ($P<0.001$) flow than IP at Snk 2 for May and June, but was significantly lower at SV 1 for July ($P=0.023$) and August ($P=0.002$).

Discussion

The results obtained suggest that altering sources of available water can have a direct impact on daily sap flow of *S. vermiculatus* in Spring Valley and Snake Valley, NV. *S. vermiculatus* is a facultative phreatophyte (McKeon et al., 2006), and therefore both precipitation and groundwater are important sources of water for this shrub. Contributions from precipitation and groundwater can vary on both a temporal and spatial scale. McLendon et al. (2008) found in Owens Valley, that the contribution from groundwater to ET increased as the depth to groundwater decreased. Furthermore, they showed that precipitation-use efficiency was greater in locations where precipitation was lowest and decreased in locations with higher precipitation. Spring Valley and Snake Valley received similar rainfall amounts during the spring and summer of 2007 (outside of the one 19 mm event at SV 1) (Figure 3-2). The biggest contrast between the two valleys was depth to groundwater and surface soil types. SV 1 had a mostly sandy soil (>85% sand with depth) with a depth to groundwater of 4.6 m, while Snk 2 had a clayey soil (>50%-75% silt/clay with depth) with a depth to groundwater of 9.3 m. The clayey

soil at Snk 2 contributed to greater water and ion retention when compared to the sandy soil at SV 1. Water retention in clay soils is a result of smaller capillary pore sizes (Kodešová et al., 2008), while ion retention is due to the higher cation exchange capacity of clay soils (Cuevas et al., 2009). These differences in soil types and depth to groundwater, in addition to plant physiological data, provided greater insight into what was driving the differences in flow between and within each treatment located at SV 1 and Snk 2.

Across both valleys, the ST shrubs showed the greatest response to treatment effect. These shrubs responded to the severing of their tap root by greatly altering their leaf morphology when compared to the TC and IP treatments. Shrubs under going Tc and IP treatment had an average leaf volume of 12 mm³ and 16 mm³, respectively, which were significantly higher ($P < 0.001$) than ST which had an average leaf volume of 6 mm³. This difference in leaf morphology of the ST group was most likely a result of carbon allocation. These plants had their taproots severed prior to leafing out and therefore carbon may have been conserved/allocated differently than it was in the TC and IP treatments. The reduction of available water enhances allocation of carbon to roots, whereas low quantum flux density promotes allocation to leaves (Lambers and Poorter, 1992). At Snk 2, however, plants had already devoted carbon to a specific leaf area, which may not have been able to be supported once the tap root was severed, resulting in a 100% complete mortality rate two weeks following root cutting. A similar response was shown by Cooper et al. (2003), who demonstrated that an abrupt decrease in the water table caused *Populus deltoides* to have a decrease in shoot water potential followed by canopy dieback.

In addition to differences in leaf morphology, ST had significantly lower sap flow than TC and IP for all measurement periods except for August, which coincided with significant differences in plant measurements. These differences during May, June and July may have been due to a combination of both increased stress and altered leaf morphology within the ST treatment. The lower flow rates of the ST treatment supported our hypothesis that a disconnect of roots to the capillary fringe above the water table occurred. A similar plant response has been suggested by Patten et al., (2008). Through the use of historic groundwater data, they estimated that a lowering of the water table in the Great Basin beyond the rooting depth may cause a shift in the vegetation away from upland phreatophytic vegetation.

Although the ST treatment showed significantly lower flow rates when compared to the TC and IP treatment, flow rates increased significantly with time. This may represent both an adjustment to an altered rooting depth and a response to rainfall. Flow rates in the ST treatment in June were significantly higher than May flow rates, while they were not significantly higher than July rates. Finally, August flow rates were higher than from all other measurement periods. The higher flow rates in August follow a 19-mm rainfall event that occurred on August 1. Because this species is a facultative phreatophyte, it can extract water from the unsaturated zone and has demonstrated the ability to respond to rainfall events. This has been shown in other species of facultative phreatophytes as well, such as *Tamarix* (Di Tomaso, 1998), which have a tendency to out compete other species which are dependent solely on groundwater in semi-arid regions. McLendon et al. (2008) also showed that when precipitation is available, Nevada saltbush communities in Owens Valley increased their relative use of precipitation derived soil

moisture by 20%. Furthermore, isotopic analysis in our study (Figure 3-8 A) showed stem exudation signatures most closely associated with rainfall. Although the coincidence of rainfall and increase stem flow seems to suggest a rainfall response, it cannot be ruled out from our data that a new taproot had once again reached the capillary fringe. Further research is needed to investigate root growth rates under varying soil textures to fully understand this treatment response.

We hypothesized that the TC and IP groups would have similar sap flow rates during the dry periods of the growing season, and that TC would have higher sap flow rates following rainfall events. Flow rates for TC at SV 1 were significantly higher than IP only during the May measurement period suggesting that this treatment had responded to an increase in vadose zone moisture due to precipitation (11 mm of rainfall prior to sap flow measurements). At Snk 2, however, TC was not significantly higher than IP until the June measurement period. This may be a delayed response to rainfall events occurring prior to the June measurement due to the high clay content (and higher water holding capacity) in the soil, though this could not be confirmed due to soil measurements only occurring at the 15 cm depth. Furthermore, the rain gage was not installed at Snk 2 until 6/1/2007, so there was no record of rainfall prior to this date. However, if rainfall had infiltrated the soil below 15 cm, the additional water source would allow shrubs in the TC treatment to transpire at a higher rate than shrubs in the IP treatment. Steinwand et al., (2006) demonstrated that in Owens Valley shrub dominated sites with a depth to groundwater greater than 5 m, $ET_{\text{groundwater}}$ was estimated in the range of 21-33%. This demonstrates a significant portion of ET occurring from precipitation and the vadose zone. The differing soil types between valleys may explain why sap flow measured in the

TC group at SV 1 had decreased during June when compared to May. For a sandy soil, percolation would have been much faster, and water may have moved below the shallow lateral rooting depth by June. In contrast, the high level of clay at Snk 2 could have caused a slower percolation rate and thus a delayed response of the TC treatment to precipitation derived soil moisture. Additionally, neither TC treatment showed a significant increase in flow following rainfall events that occurred in early August. This was especially surprising at SV 1, considering the rainfall amount was 19 mm. It may be that the large variability (note error bars in Figure 3.10 A) contributed to the non-significance of the TC flow rate over IP. At Snk 2, however, non-significance between TC and IP in August could be a combination of smaller rainfall events, coupled with soil texture and a deeper vadose zone. The smaller rainfall events may not have penetrated deep into the soil before evaporation had occurred. Furthermore, the deeper vadose zone at this site was not entirely monitored and therefore it is impossible to infer what the soil moisture was in the profile. It has been demonstrated by Donovan et al. (1996) that *S. vermiculatus* has the greatest root density within the upper 1.0 m of soil and decreasing root density with depth. However, they also found roots in augured holes as deep as 5 m. Our results would suggest that greasewood accessed groundwater even at a depth of 9 m at the Snk 2 site..

Differences in flow rates between SV 1 and Snk 2 can be partially explained by site differences. We hypothesized that, due to the deep water table and the higher clay content in the soil at Snk 2, flow rates there would be highly dependent on vadose zone soil moisture early in the spring (recharge from mountain snowmelt combined with precipitation would result in high vadose zone moisture) and that plants would begin to

rely on a higher amount of groundwater use as the vadose zone moisture became depleted. This is supported by Lamontagne et al. (2005), who demonstrated patterns of soil matric potential that were consistent with the tendency of facultative phreatophytes to gradually revert to deeper soil moisture and groundwater use as vadose zone soil moisture became depleted. In contrast, the sandy soil and shallow water table at SV 1 would result in a combination of vadose zone and groundwater extraction throughout the growing season. The result would be higher sap flow in the SV 1 treatments during the spring when compared to Snk 2, which would gradually become similar as plants at Snk 2 increased groundwater uptake. This hypothesis was supported by the TC treatments. During the May measurement period, plants at SV 1 had a higher sap flow, while during the remainder of the growing season there were no significant differences between TC transpiration flows. Additionally, sap flow in the IP treatment was lower at Snk 2 during the spring when compared to SV 1; however transpiration increased in July and August. This may represent additional vadose zone uptake (much deeper vadose zone at Snk 2 when compared to SV 1) in the IP group at Snk 2 that was not occurring at SV1.

The greatest evidence that this hypothesis was valid can be seen by comparing the flow rates of the IP treatment between valleys. The IP flow rates at Snk 2 were significantly lower during the May and June measurement periods, but significantly higher during the July and August measurement periods when compared to the IP treatment at SV 1. We hypothesized that flow rates in the IP treatment would be higher at the SV 1 site during the spring due to the shallower water table and similar in flow during the latter part of the growing season compared to Snk 2. However, this hypothesis was not completely supported, as sap flows at Snk 2 IP became higher than SV 1. It is unclear

as to why this phenomenon occurred, but again this could demonstrate a switch in the source of water used by *S. vermiculatus* that was not detected by the isotopic analysis (which contained summer measurements only), in addition to contributions from a much deeper vadose zone at Snk 2 that was not fully monitored. The tendency of plants to preferentially use precipitation/vadose zone water (when available) over deep ground water has been shown in previous studies (McLendon et al., 2008). Furthermore, Lautz (2008) demonstrated that following precipitation events, facultative phreatophytes had a decrease in groundwater ET, and an increase in unsaturated soil water ET.

Soil moisture at the 15 cm depth under the IP treatment did not differ significantly throughout the growing season at SV 1 (Fig 3-6 A). However, the soil moisture in the IP treatments at Snk 2 significantly decreased from May until June, and then remained unchanged for the remainder of the monitoring period. Although soil moisture redistribution can not be ruled out, the change might suggest that these plants had active root water uptake in the shallow vadose zone soil during the spring and switched to a greater ground water contribution and deep vadose zone soil moisture in June. The deeper vadose zone that possessed higher clay content at Snk 2 could contribute to higher flow rates than were observed in the IP treatment at SV 1. Finally, the data revealed a temporal effect on sap flow in the IP treatment at Snk 2, but not at SV 1. Flow rates at SV 1 did not differ significantly in the IP treatment throughout the growing season. However, at Snk 2 the May and June IP flow rates were significantly lower than the July and August flow rates, which suggests that some additional water source was being utilized.

This study demonstrates that the facultative phreatophyte *S. vermiculatus* growing in Spring Valley and Snake Valley, NV utilizes water from both the vadose zone and

groundwater. Furthermore, the data indicates that when precipitation is prevented from infiltrating, it has a smaller effect on daily flow rates, than when taproots are severed and plants become decoupled from groundwater (ST flow rates vs. IP flow rates). Differences in sap flow between treatments in the two valleys can be somewhat explained by differences in soil texture and depth to groundwater. However, it appears that the differences in sap flow cannot be fully explained without monitoring the entire vadose zone in each valley, rather than just the upper 15 cm. The differences in flow rates observed between treatments may provide valuable information on how this species might respond to a rapidly declining water table. Such information should be useful in the management of groundwater levels and vegetation within Spring Valley and Snake Valley shrub communities. If the goal of management is to extract groundwater while sustaining the plant community, further studies will need to be completed to determine critical groundwater depths and extraction rates, beyond which site specific species begin to show signs of stress leading to potential die back, death and/or displacement.

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CHAPTER 4

GENERAL DISCUSSION

The sustainability of potable water has come to the forefront of concern for water managers across the desert southwest. A long hydrologic drought coupled with population growth to many of the regions major cities, has led water districts to look toward alternative methods of providing this natural resource to its citizens. One method, which has received much recent attention in Las Vegas, NV, is to build a pipeline and move ground water from Spring Valley and Snake Valley, which are located approximately 250 miles northeast of the city. This method is not uncommon, noting the movement of water that occurred from Owens Valley, CA to Los Angeles, CA in the early 1900s. Water is still piped from Owens Valley today, but despite several decades of management, the impacts of water redistribution on the vegetation and ecosystem processes are still highly uncertain (Pataki et al., 2008). Understanding the effects of moving water from regions such as Spring Valley and Snake Valley on the natural ecosystem is socially, agriculturally, and biologically important. This dissertation research examined the plant water use and dependence on groundwater of the natural vegetation (with special emphasis on *Sarcobatus vermiculatus*) located in these regions by integrating plant ecophysiology, ecohydrology, and atmospheric science. The knowledge gained from investigating vegetative water use under natural settings should provide greater insight into what might happen when such ecosystems have their

hydrology altered. Our long term goal is to continue to try to understand the ecology and hydrology of the valleys in the face of climate change and human altered landscapes.

Scaling Canopy Measurement to Basin Wide Measurements

Determining evapotranspiration (ET) amounts is an important component in estimating a regional water balance. However, techniques used to estimate ET can face spatial, temporal, methodological, and/or logistical limitations (Anderson and Goulden, 2009). For ET estimates in Spring Valley and Snake Valley, scaling canopy measurements to basin-wide measurements represents a significant challenge. We addressed this scaling issue by conducting an assessment of sensible heat with an eddy covariance system and a large aperture scintillometer (LAS). In Chapter 2, we showed that LAS can be effectively used to estimate sensible heat over large heterogeneous pathlengths in the Great Basin. This was demonstrated by the significant correlations between sensible heat from an eddy covariance (EC) station and the LAS (Figure 2-8) during the growing season of 2005. The sensible heat from the LAS can be used in the energy balance equation to estimate ET (Chapter 2, equation 1). This technique allows for a more complete scaling of ET as one goes from small pathlength estimates from the EC, to large pathlength estimates from the LAS, to basin-wide estimates from satellites. Future research is needed, however, to address the following questions:

1) Can LAS accurately estimate sensible heat over heterogeneous elevations?

Kleissl et al. (2009) demonstrated over homogenous slant paths in NM, good agreement between the regression and correlation coefficients of four scintillometers. However,

additional techniques such as Landsat and EC stations were not included for comparison in that study.

2) What is the sensitivity of the system to advection from adjacent landscapes?

Hoedjes et al. (2002) found good results using the LAS over an irrigated wheat field which was affected by regional advection. Thus as long as the beam is located within the blending region of the boundary layer, advection could have minimal effects on sensible heat estimation, but a more robust investigation may give more insight.

3) Can the LAS effectively replace the EC system and be used in conjunction with satellite data to estimate basin-wide ET? Currently, studies have shown that LAS can be used to validate remote sensing data such as surface temperature (Watts et al. 2000; Lagouarde et al. 2002). However, research has yet to be completed estimating basin-wide ET using only LAS and remote sensing.

Effect of Differential Water Sources on *Sarcobatus vermiculatus*

In Chapter 3, I focused on investigating the water use pattern (sap flow) of *Sarcobatus vermiculatus* under differential water resource availability. Based on the findings of this study, it was apparent that water use of this facultative phreatophyte depended on both groundwater and vadose zone soil moisture, which in turn were dependent on site characteristics such as soil texture and depth to groundwater. These findings showed that sap flow in the IP treatments of shrubs located at Snk 2 (depth to ground water 9.31 m), were lower than in shrubs located at SV 1 (depth to groundwater 4.66 m) during the May and June measurements, but were higher during the July and August periods. This suggested that perhaps these plants were initially relying on deep

vadose zone moisture early in the growing season, and relied on groundwater uptake later in the growing season when environmental demand was at its highest. This conclusion was supported by a decline in the water table and increased groundwater oscillations toward the end of summer at both sites.. Canham et al. (2008) have suggested that facultative phreatophytes at a dune site in Australia, with a deep water table, were able to form roots deep within the vadose zone. We did not monitor the deep vadose zone located at Snk 2, and this proves to be an important component for future research in fully understanding root water uptake in *S. vermiculatus*. Furthermore, SV 1 soil texture was classified as sandy, while Snk 2 soil texture was mostly clay. The IP treatment was designed to prevent infiltration, but soil moisture was only monitored to 15 cm. An additional question that needs to be answered is: to what extent can rain water infiltrate these different soil types before being either evaporated or intercepted by shrub roots? We have shown through isotopic analysis that xylem water following rainfall events contained deuterium signatures most closely related to rainwater, suggesting that this plant does indeed respond to episodic precipitation events during the summer months. Furthermore, soil EC and Na data (Figure 3-7 A-B) also support water uptake occurring in the upper 4.5-m of the profile. Finally, we have shown that severing the tap root of these plants, and thus effectively removing them from a groundwater source, has a profound impact on their daily sap flow rates (Figure 3-8 A-B). However, we were unable to answer the question of how long it would take for a new tap root to reach the water table, which could lead to vital information related to how fast water table drawdown associated with groundwater pumping should be allowed. All of our plants from the ST treatment had died at Snk 2, but at SV 1 there appeared to be an increase in

sap flow from July-August (although it was non-significant). We were unable to determine whether this apparent increase was a response to increased rainfall (since TC seemed to have an increase in flow as well) or whether roots had reached the capillary fringe at this shallow groundwater site. Future research examining the growth rate of tap roots in *S. vermiculatus* located in different soil textures is needed.

In this dissertation study we examined the water use of shrubs located in the Great Basin, NV. The results demonstrated that LAS can be effectively used over heterogeneous vegetation to estimate sensible heat which was in good agreement with sensible heat obtained from an eddy covariance station. This study demonstrated that the LAS method could be used to scale energy processes from small to large pathlengths, with the potential for use in conjunction with satellite data to estimate a basin-wide water balance. Furthermore, we examined more closely the potential impact of a water table drawdown by investigating the water use of the facultative phreatophyte *S. vermiculatus*. Research has shown that understanding these processes could prove vital in the mitigation of water extraction from valleys such as Spring and Snake (Simpson and Duell, 1985; Dileanis and Groeneveld, 1989; Steinwand et al., 2001; Steinwand et al., 2006). We proposed several additional questions that need to be answered to fully understand the physiology and hydrology of these systems, before a proper mitigation plan can be put in use. However, the knowledge gained from this research can provide the groundwork for such studies, and may give insight into additional equally important questions. It is the hope of this author, that this research will continue to be a focus in both academia and industry so that these natural resources may be preserved in the face of anthropogenic and global climate change.

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