



## Using stable oxygen isotopes to quantify the water source used for transpiration by native shrubs in the San Luis Valley, Colorado U.S.A.

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### Abstract

An understanding of the water source used by phreatophytic desert shrubs is critical for understanding how they function and respond to man-caused groundwater drawdowns. Shrubs can use primarily groundwater, precipitation recharged soil water, or a mixture of the two. If shrubs use primarily groundwater, a water table decline may reduce water availability and lead to high plant mortality. However, if shrubs can acquire precipitation recharged soil water, then groundwater decline could have less impact on plants. This study took place in the San Luis Valley, a large, arid, high elevation closed basin in south-central Colorado. We examined stable oxygen isotopes in precipitation, soil water from several depths, groundwater and plant xylem water to identify the likely water sources for the three most abundant shrubs in the valley: *Sarcobatus vermiculatus* (Hooker) Torrey, *Chrysothamnus nauseosus* (Pallas) Britton subsp. *consimilis* (Greene) Hall & Clements, and *Chrysothamnus Greenei* (Gray) Greene. *C. Greenei* is not known to be phreatophytic while *S. vermiculatus* and *C. nauseosus* may be phreatophytic. Mean annual San Luis Valley precipitation during the two years of study was 121 mm, with 67% occurring during the summer monsoon season of July through September. We found differences in water acquisition patterns by species, season, and along a depth to water table gradient. *C. Greenei* only occurred in sites with a water table > 2.0 m deep, and utilized only soil water recharged by precipitation. At sites with a water table less than 2 m depth, *S. vermiculatus* and *C. nauseosus* utilized soil water from the top 0.5 m and shallow groundwater during the pre-monsoon and monsoon periods. A more complex water use pattern was found at sites with a water table deeper than 2 m. *S. vermiculatus* and *C. nauseosus* used both deep soil water and groundwater during 1996. During the pre-monsoon period in 1997, both shrubs utilized predominantly groundwater. However, during the 1997 monsoon season both species switched to utilize primarily precipitation recharged water acquired from the upper 0.3–0.4 m of soil. This is the first report that *C. nauseosus* can utilize summer precipitation. Our results support the hypothesis that plants utilize more summer rain recharged soil water in regions receiving a substantial proportion of annual precipitation during the summer.

### Introduction

Evapotranspiration accounts for ~80% of the water output from hydrologically closed basins, such as the northern San Luis Valley in Colorado (Emery, 1969). Evaporation occurs from upper soil layers recharged by precipitation as well as surface water recharged

by precipitation or snowmelt runoff from adjacent mountain ranges. Phreatophytes growing on the basin floor can transpire water from these sources, although groundwater and its capillary fringe is reported to be the most important water source for many phreatophyte species in arid regions (Ehleringer et al., 1991), including the dominant native shrubs in the San Luis Valley *Sarcobatus vermiculatus* (Hooker) Torrey and *Chrysothamnus nauseosus* (Pallas) Britton subsp. *con-*

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*similis* (Greene) Hall & Clements. Where a high proportion of annual precipitation occurs during the summer, phreatophytes may also acquire precipitation recharged soil water (Dawson and Pate, 1996).

There is increasing pressure in many arid regions of the western US, including the San Luis Valley, to increase groundwater use for agriculture and urban supplies. Understanding the proportion of groundwater vs. precipitation recharged soil water used by phreatophytes is critical for constructing accurate groundwater models and predicting the influence of human induced water table changes on phreatophytes (Cooper et al., 2003; Scott et al., 1999). If phreatophytes utilize primarily groundwater then lowering the water table could induce plant dieback and mortality, reducing annual evapotranspiration. However, if these species can utilize soil water recharged by precipitation, then groundwater declines may have less effect on plant health and evapotranspiration rates.

*Chrysothamnus nauseosus* [family *Asteraceae*] is one of the most deeply rooted and least water-stressed shrub species in the western U.S. even though its use of water is thought to be relatively inefficient (Branson et al., 1976; Flanagan et al., 1992). Stable isotope studies of *C. nauseosus* water sources suggest that it utilizes primarily groundwater, and acquires little summer rain recharged soil water, even when it is abundantly available (Donovan and Ehleringer, 1994; Ehleringer et al., 1991; Flanagan et al., 1992; Flanagan and Ehleringer, 1991; Lin et al., 1996). A water table drawdown experiment in the Owens Valley, California produced high mortality rates in *C. nauseosus*, indicating its reliance on groundwater (Sorenson et al., 1989). However, a similar drawdown experiment conducted in the San Luis Valley did not reduce *C. nauseosus* evapotranspiration rates and produced no mortality, suggesting that it did not rely solely on groundwater (Charles, 1987). The most common subspecies of *C. nauseosus* occurring in many arid basins with saline soils in the western US is *Chrysothamnus nauseosus* (Pallas) Britton ssp. *consimilis* (Greene) Hall & Clements, commonly known as salt rabbitbrush. However, few ecological studies have identified *C. nauseosus* to subspecies.

*Chrysothamnus greenei* (Grey) Greene [family *Asteraceae*] and *Sarcobatus vermiculatus* [family *Chenopodiaceae*] are common shrubs that occur in the San Luis Valley. These species have received little research attention compared to other desert shrubs. *S. vermiculatus* covers 4.8 million ha in the western U.S. (Mozingo, 1987), grows preferentially on

saline-sodic soils (Branson et al., 1976), is relatively flood intolerant (Groeneveld and Crowley, 1988), and has roots that can reach 6–17 m deep (Meinzer, 1927). Evapotranspiration rates and leaf area of *S. vermiculatus* were unaffected by the Owens Valley water table drawdown experiment (Sorenson et al., 1989), however, the San Luis Valley drawdown experiment reduced evapotranspiration rates for this species (Charles, 1987). *C. greenei* is not known to be a phreatophyte and its water acquisition patterns are unknown.

The objectives of our study were to determine: (1) the relative importance of groundwater for transpiration by native shrubs in the San Luis Valley, (2) whether water table depth influenced the proportion of groundwater used, and (3) whether any study species utilized summer monsoon precipitation.

## Materials and methods

### Study sites

The San Luis Valley in south central Colorado is the largest intermountain basin in the Rocky Mountain system, ~145 km north to south and 30 to 80 km east to west. The valley floor is nearly flat, and bordered by the San Juan Mountains on the west and the Sangre de Cristo Mountains on the east, with both ranges having peaks >4200 m elevation. The Rio Grande flows east from the San Juan Mountains, crosses the middle of the San Luis Valley where it turns south. The San Luis Valley north of the Rio Grande, an area of ~7,600 km<sup>2</sup>, is a closed basin with no surface water outlets. Mountain snowmelt runoff feeds a number of streams that enter the Closed Basin. These streams flow over mountain front alluvial fans where they recharge groundwater aquifers. During the spring snowmelt period streams may flow far into the Closed Basin, while during the summer, fall and winter, streams disappear on the alluvial fans.

The valley floor receives ~150 to 250 mm of annual precipitation while adjacent mountains receive ~0.75 to >2 m (Charles, 1987). Despite the low annual precipitation, shallow groundwater (<1.0 to 6.0 m) occurs throughout the closed basin area of the San Luis Valley, and high evaporation rates have produced saline soils. The valley floor vegetation is dominated by halophytes, which may also be phreatophytes, particularly *S. vermiculatus* and *C. n. consimilis*, as well as the grasses *Distichlis stricta*

(Torrey) Rydberg [family *Poaceae*] and *Sporobolus airoides* (Torrey) Torrey [family *Poaceae*]. These four species dominate the vegetation of non-wetland and non-agricultural lands throughout study area, making it floristically similar to other Great Basin Province closed basins. For example, these same four species are abundant in the Owens Valley in California (Groeneveld et al., 1985).

Plant, soil, and groundwater samples for isotopic analysis were collected from six sites during 1996, and five sites during 1997 (Table 1). The 1996 study sites varied in their soil characteristics, depth to water table, vegetation composition and leaf area. The 1997 sites represented a water table depth gradient from < 1.0 to ~ 15 m, and all sites were dominated by *S. vermiculatus*. These sites also represented a soil salinity and texture gradient, with the most saline and finest grained soils occurring at sites with the shallowest water table depths.

#### *Stable isotope analyses*

Stable isotope analysis has been widely utilized over the past 15 years to provide insight into the seasonal pattern of plant water sources (Dawson and Ehleringer, 1991; Ehleringer et al., 1991; Thorburn and Walker, 1993; White et al., 1985). Most plant water source studies utilize stable isotopes of hydrogen (e.g., Donovan and Ehleringer, 1994; White et al., 1985) because the atomic mass difference between hydrogen (H) and deuterium (D or  $^2\text{H}$ ) is larger than that between the stable oxygen isotopes  $^{18}\text{O}$  and  $^{16}\text{O}$ . However, Lin and Sternberg (1993), Lin and Sternberg (1994), Sternberg et al. (1991), and Sternberg and Swart (1987) have demonstrated significant hydrogen isotopic fractionation during water uptake by certain halophytes from discrimination against D by roots associated with salt filtration. Thus, plant stem water may not reflect its source water relative to D and H. Because all San Luis Valley study plants are halophytes and could possibly fractionate against D, we used oxygen isotopes to determine plant water sources. We analyzed stable oxygen isotope ratios of water extracted from soil horizons and groundwater to characterize potential water sources for plants, which were compared with stable oxygen isotope ratios of plant xylem water.

During 1996, samples were collected from each study site approximately every three weeks from May through September, covering the entire growing season (Table 1). During 1997, we collected samples on

27 June and 13 August (Table 1). The June samples were collected during a five-week rainless spell and volumetric soil water content in the upper 0.6 m of soil was at its annual low. The August samples were collected during a period of monsoonal rains, and ~ 31 mm of rain had been received in the previous three weeks.

Groundwater samples were collected from monitoring wells constructed of 3 cm diameter slotted PVC pipe after first emptying the casing at least five times. Plant samples were collected by cutting fully suberized stem sections from the base of plants. Samples were cut from three plants of each species, considered within site replicates and separated by at least 10 m, during each sample period. Rain was sampled on five occasions during 1996 in an air and water tight tube with a funnel attached to the top, and a thick layer of oil inside the tube. To reflect the large contribution of mountain snowmelt water to the ground water isotopic signature, North Crestone Creek water was collected where it exits its bedrock canyon. We also collected one sample from Saguache Creek near the town of Saguache. Crestone Creek and Saguache Creek are representative of perennial streams entering the northern San Luis Valley.

Soil samples were collected using a hand auger. In 1996 samples were initially collected from two depths, 0.2–0.3 m and 0.5–0.6 m, thought to represent the near surface and intermediate rooting zones. However, when the first samples were analyzed we found that many of the plant xylem water samples were more enriched in  $\delta^{18}\text{O}$  than groundwater or either soil horizon, suggesting that plants were acquiring water from more shallow soil horizons. We altered our sampling approach and collected soil in 0.1 m increments from the surface down to 0.6 m depth. Two soil cores were taken at each site on each sample date and samples were analyzed separately. In 1997 soil water was collected at 0–0.2, 0.2–0.5, 0.9–1.1 and 1.9–2.1 m depths. All water, plant, and soil samples were packaged immediately in airtight bottles and refrigerated until analyzed.

Oxygen isotope ratios were determined by Mountain Mass Spectroscopy (Evergreen, CO) using a VG Sira mass spectrometer. Cryogenic distillation was used to collect water from soil and plant samples (Ehleringer and Osmond, 1989). We calculated the isotope ratio relative to that of a standard,  $\delta^{18}\text{O}$ , as:  $\delta^{18}\text{O}(\text{‰}) = \{[(^{18}\text{O}/^{16}\text{O})_{\text{sample}}/(^{18}\text{O}/^{16}\text{O})_{\text{standard}}]^{-1} \times 1000$ , using Standard Mean Ocean Water (SMOW) as our standard (Dawson, 1993).

Table 1. Physical and biological characteristics of study sites during 1996 and 1997. Mean water table depth (WT) in m, soil electrical conductance EC (mS/cm<sup>2</sup>), soil texture (SL = sandy loam, SCL = sandy clay loam, LS = loamy sand), and soil pH. Vegetation characteristics include leaf area index (LAI) and dominant plant species (*Sarcobatus vermiculatus* is Sv, *Chrysothamnus nauseosus* is Cn, *Distichlis stricta* is Ds, *Sporobolus airoides* is Sa, *Chrysothamnus greenei* is Cg, *Bouteloua gracilis* is Bg). Plant species analyzed isotopically are indicated by \*

Site	Year	WT	EC	Texture	pH	LAI	Species
Salt	1996	1.0	5.87	SCL	7.79	0.22	Sv*, Ds, Sa
Crestone	1996	1.5	5.36	SCL	9.80	0.53	Sv*, Cn*, Sa
Thicket	1996	1.5	4.51	SCL	8.09	1.26	Sv*, Cn*
Gardner	1996	2.2	4.58	SCL	9.93	0.16	Sv*
Hickey Bridge	1996, 1997	4.3	1.52	SL	8.24	0.23	Sv*, Cn*, Cg*, Bg
Greasewood	1996, 1997	13.0	0.23	SL	7.94	0.26	Sv*, Bg
Flat	1997	0.9	9.20	SCL	9.96	0.34	Sv*, Ds
Saguache	1997	2.1	9.89	SC	8.51	0.44	Sv*, Cn*, Ds, Sa
Well 5	1997	7.1	0.89	SL	8.73	0.18	Sv*, Bg, Cg*

### Ancillary measurements

Leaf area index (LAI) was measured non-destructively by repeated use of a point frame following methods of Groeneveld (1997). From each study site three line transects, each 100 m long, were established. Each transect was oriented into a predominant wind direction to reflect LAI in the area of wind fetch. At the 0 point and every 1 m along each transect, a pin was dropped (a total of 303 points), and all hits on plant leaves were recorded. LAI was calculated as:  $LAI = (Hits/303) \times 2$ .

All statistical analyses were performed using SYSTAT 10.0 (SPSS, 2000). ANOVA was used to test for differences in isotopic composition of groundwater, soil water and xylem water.

## Results

### Precipitation and groundwater

Mean annual precipitation at the Center weather station (1980 to 1996) in the San Luis Valley was 180 mm. Winters are dry, with ~70% of annual precipitation occurring in the growing season and ~50% occurring from rains driven by the southwestern North America monsoon flow in July, August and September (Figure 1). In 1995, a normal year in the San Luis Valley, 161 mm of precipitation fell, with 87 mm falling in the late summer. Spring and early summer 1996 were moderately dry with ~20 mm of rain falling in March and April, followed by nearly 8 rainless weeks.

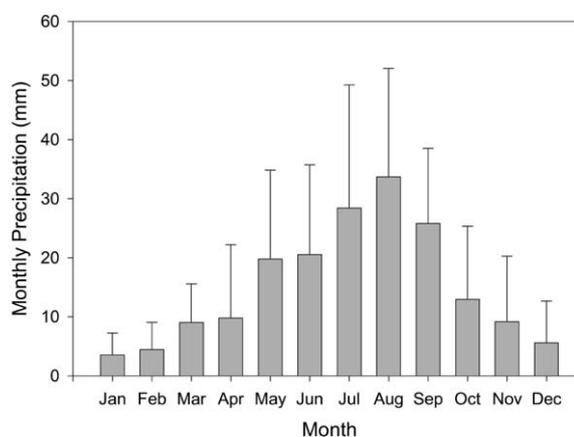


Figure 1. Mean monthly precipitation at Center, Colorado weather station located in the center of the San Luis Valley. Bars indicate +1 standard deviation of the mean.

Twenty-six mm of rain fell during the last two weeks in June, and an additional 30.5 mm fell during the late summer monsoon season, for an annual total of 97 mm. In 1997, conditions during winter and spring were extremely dry, with a six-month rainless period that ended in May, followed by greater than normal summer precipitation of 99 mm.

$\delta^{18}O$  of collected precipitation was highly variable (Table 2). The two June samples were from afternoon thunderstorms on hot days and the water was enriched in  $\delta^{18}O$ , while three rain samples collected during cool days with strong monsoon rainstorms were among the most depleted water samples analyzed.

Table 2. Mean, standard deviation, and range of  $\delta^{18}\text{O}$  for groundwater, precipitation and stream water samples collected during 1996 and 1997

	<i>n</i>	Mean (sd)	Range
Groundwater	28	-13.24 (1.36)	-15.77 to -11.39
1996	22	-12.83 (1.00)	-11.39 to -14.97
1997	6	-14.72 (1.53)	-12.44 to -15.77
N. Crestone Creek	2	-14.03	-14.75 to -13.31
Saguache Creek	1	-13.80	
June 1996 Precipitation	2	-2.27 (7.02)	-8.35 to 3.81
Aug-Sept 1996 Precipitation	3	-15.49 (0.36)	-15.20 to -15.98

Groundwater was isotopically depleted with no significant differences in  $\delta^{18}\text{O}$  between study sites ( $P < 0.05$ ). Ehleringer and Dawson (1992) report that the isotopic composition of groundwater is a weighted average of long-term precipitation input. However, since mean annual precipitation onto the San Luis Valley floor is low, direct recharge of the groundwater table by precipitation is probably uncommon. Most groundwater is derived from high mountain snowmelt runoff flowing in discrete streams from the mountain front and onto broad, coarse-textured alluvial fans where much of the water is lost to the aquifers. Water samples collected from North Crestone and Saguache Creeks have  $\delta^{18}\text{O}$  values similar to groundwater, indicating that these streams likely recharge San Luis Valley groundwater (Table 2).

#### $\delta^{18}\text{O}$ of soil water

During 1996 soil water had a monotonic decline in  $\delta^{18}\text{O}$  from the soil surface to the water table at all sites (Figure 2). The  $\delta^{18}\text{O}$  of upper soil water (0–0.2 m depth) was always more enriched, due to evaporation, than lower soil horizons and groundwater (Allison et al., 1983). Deeper soil (0.3–0.6 m depth) was usually more depleted in  $\delta^{18}\text{O}$  than near surface soils, but more enriched than groundwater (Figure 2). Soils at this depth had similar seasonal patterns of  $\delta^{18}\text{O}$  at all sites, suggesting they were influenced by evaporative enrichment, although to a lesser degree than more shallow soil layers.

In June 1997 soil water at the Hickey Bridge, Well 5 and Greasewood sites, which had the deepest water tables, had a mean  $\delta^{18}\text{O}$  of  $-4.4\text{‰}$ , which was significantly higher ( $P = 0.01$ ) than the more shallow water table sites Flat and Saguache, where the mean  $\delta^{18}\text{O}$  was  $-10.2\text{‰}$  (Figure 3). Soils in the upper

0.5 m had significantly different ( $P < 0.001$ ) mean  $\delta^{18}\text{O}$  values in June,  $-1.9\text{‰}$ , compared with  $-9.3\text{‰}$  in August. For sites with deeper water tables, soil water was more depleted in  $\delta^{18}\text{O}$  in August than in June ( $P = 0.007$ ). This trend was not apparent for sites with shallow water tables, where there was no significant difference in the isotopic values measured in August and in June ( $P = 0.80$ ) (Figure 3B). This suggests that the soil isotope chemistry of sites with water tables  $< 2$  m below the soil surface may be controlled more by the capillary rise of groundwater than precipitation.

#### Seasonal patterns of $\delta^{18}\text{O}$ in plant xylem water

The  $\delta^{18}\text{O}$  of *S. vermiculatus* xylem water during 1996 ranged from  $-10\text{‰}$  to  $-3\text{‰}$  although we did not observe any seasonal trends (Figure 4A). Two plant samples that were more enriched in  $\delta^{18}\text{O}$  were collected in July following the largest rain event of 1996. Mean  $\delta^{18}\text{O}$  for *S. vermiculatus* was more enriched than groundwater during all sample periods, and was most similar to water in the upper 0.4 m of soil profile (Figure 4A). The mean  $\delta^{18}\text{O}$  of *S. vermiculatus* for the Hickey Bridge and Greasewood sites was  $-8.9\text{‰}$ , with xylem water being most enriched early in the season and more depleted as the season progressed (Figure 4B). The mean  $\delta^{18}\text{O}$  for these two sites were also more enriched than groundwater, and most similar to mean soil water at 0.4–0.6 m depth (Figure 4B).

The mean  $\delta^{18}\text{O}$  for *C. nauseosus* xylem water during 1996 was  $-8.9\text{‰}$ , which was more enriched than groundwater and most similar to mean soil water  $\delta^{18}\text{O}$  at 0.2–0.4 m depth (Figure 5). On 16 July 1996 Thicket had a  $\delta^{18}\text{O}$  of  $-1.7\text{‰}$ , suggesting water uptake from near surface soils.

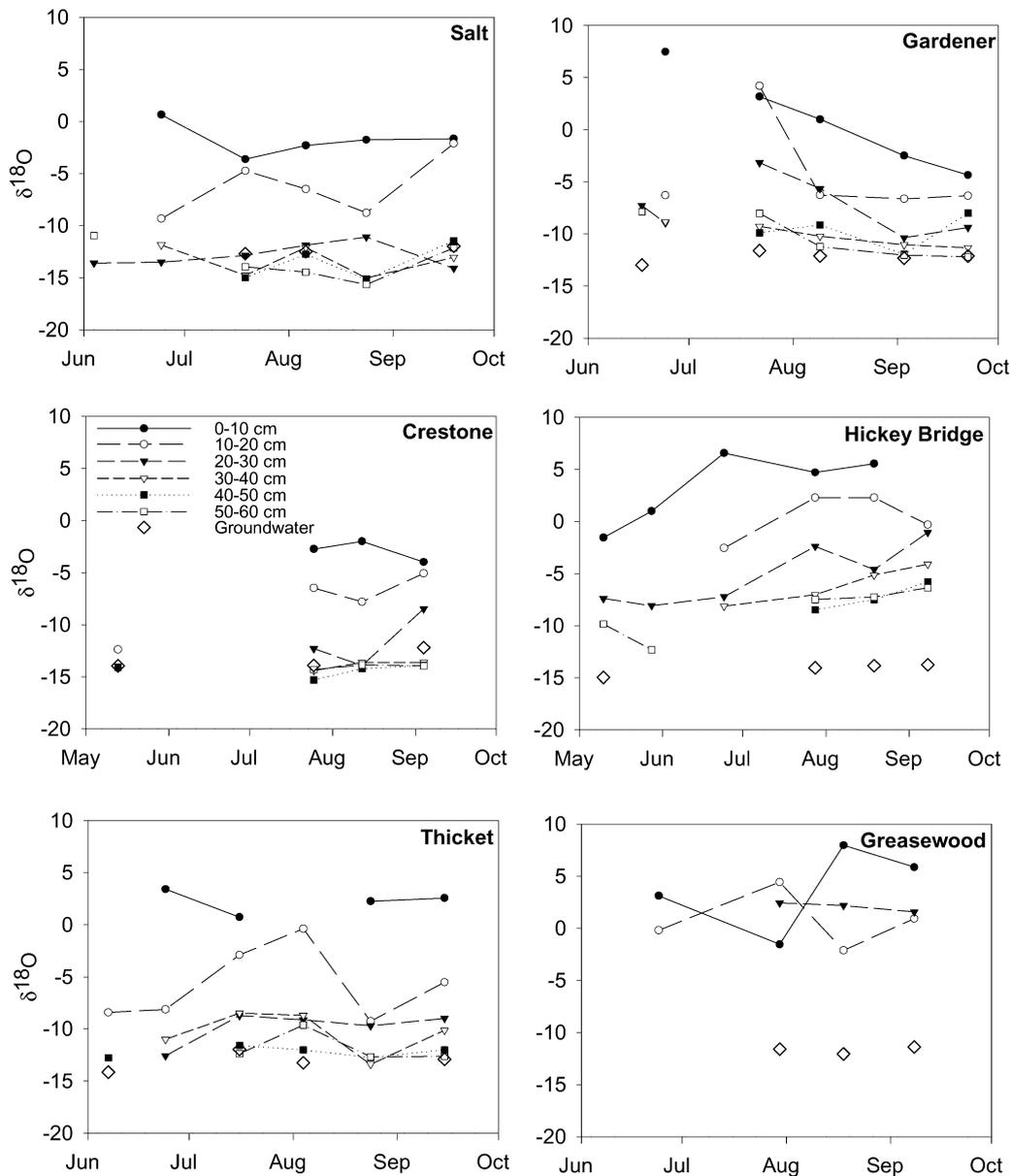


Figure 2. (A–F). Mean  $\delta^{18}\text{O}$  (‰) for groundwater and soil water by depth during 1996.

#### Patterns of $\delta^{18}\text{O}$ in plant xylem water along a water table gradient

During the June 1997 sample period *S. vermiculatus* and *C. nauseosus* xylem water  $\delta^{18}\text{O}$  ranged from  $-12.8$  to  $-14.5$ ‰ suggesting that plants were primarily acquiring deep soil water or groundwater, which had a  $\delta^{18}\text{O}$  of  $-12.5$  to  $-15.5$ ‰ (Figure 6A,B). Xylem water of plants growing on deeper water tables

sites generally was more depleted in  $\delta^{18}\text{O}$  than plants on sites with more shallow water tables.

There were no significant differences ( $P > 0.05$ ) in the  $\delta^{18}\text{O}$  of *S. vermiculatus* and *C. nauseosus* water between the June and August 1997 sample periods for sites with a water table less than 2 m deep (Figure 6A, 7B). Xylem water  $\delta^{18}\text{O}$  for both species was isotopically most similar to soil water at 0.2–0.5 m depth. During August xylem water of *S. vermiculatus* and *C. nauseosus* was significantly more enriched than

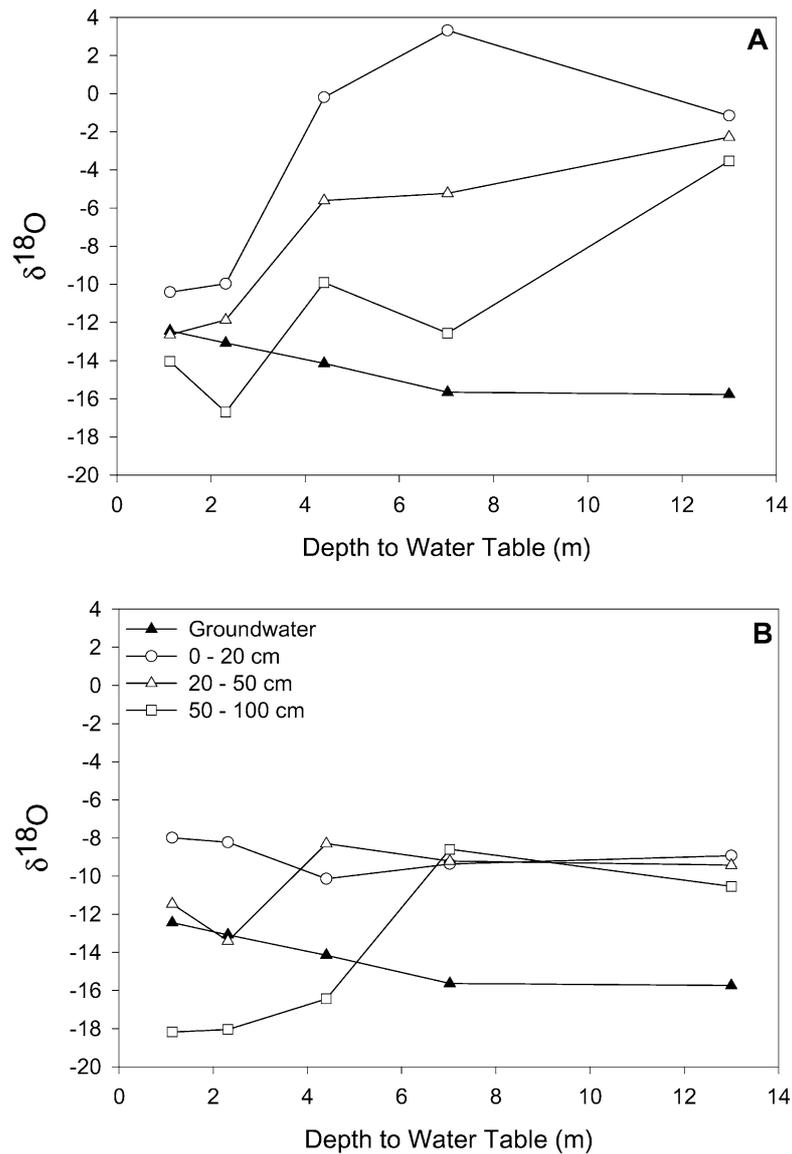


Figure 3. Mean  $\delta^{18}\text{O}$  (‰) for groundwater and soil water by depth during 27 June 1997 and 13 August 1997.

during the June sample period, with a mean  $\delta^{18}\text{O}$  of  $-9.2\text{‰}$  ( $P = 0.003$ ) (Figure 6A, 7B).

*Chrysothamnus Greenei* xylem water had a  $\delta^{18}\text{O}$  of  $-1.5$  to  $-7.2\text{‰}$  during 1997 (Figure 6C) closely matching the  $\delta^{18}\text{O}$  of soil water at 0.2–0.5 m depth (Figure 3). *C. Greenei* xylem water was slightly more enriched during the August than June sample period.

## Discussion

### Sources of soil water

At study sites with water tables within 2 m of the soil surface, water in soil layers 20–30 cm below the ground surface down to the water table were isotopically similar to groundwater, suggesting that these soils were recharged primarily by the capillary rise of groundwater. Precipitation recharged soil water as well as evaporation enriched soil water was available within the top 20 cm of soil. In trenches excavated

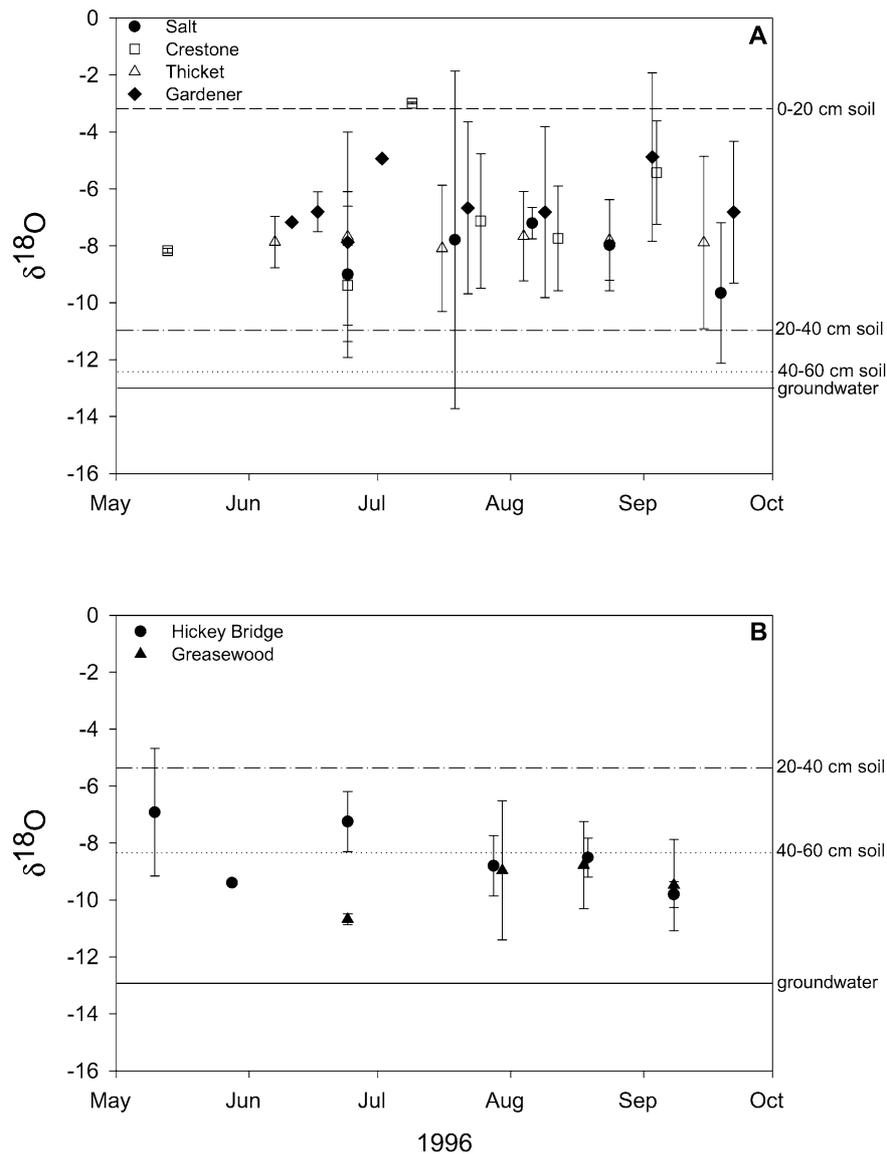


Figure 4. Mean ( $\pm 1$  se)  $\delta^{18}\text{O}$  (‰) for *Sarcobatus vermiculatus* during 1996 for A) sites with groundwater 2 m or less, and B) site with groundwater deeper than 2 m.

to analyze phreatophyte root systems we identified what appeared to be permanent dry soil layers between the zone of rain recharged and groundwater recharged soils at sites with water tables  $> 4$  m deep (Cooper and Chimner, unpublished data). Thus, for deep groundwater sites, phreatophytes have two spatially separated and distinctive zones from which water can be acquired.

Groundwater depth controlled the influence of monsoon rains on the  $\delta^{18}\text{O}$  of shallow soil layers. For example, the mean  $\delta^{18}\text{O}$  of water in the top 0.2 m of

soil at deep water table sites was  $0.7\text{‰}$  in June, while it was  $-9.5\text{‰}$  in August 1997 after monsoon rains had fallen. In contrast the  $\delta^{18}\text{O}$  of soil water was similar at these two times in sites with a water table within 2 m of the soil surface, suggesting that capillary rise from the water table controls soil water isotope chemistry in shallow soil horizons. Thorburn et al. (1993) found that capillary rise could recharge soils to within 0.5 m of the soil surface from a water table at least 3 m deep at an Australian study site. Thus, near surface soil layers in our San Luis Valley study sites with

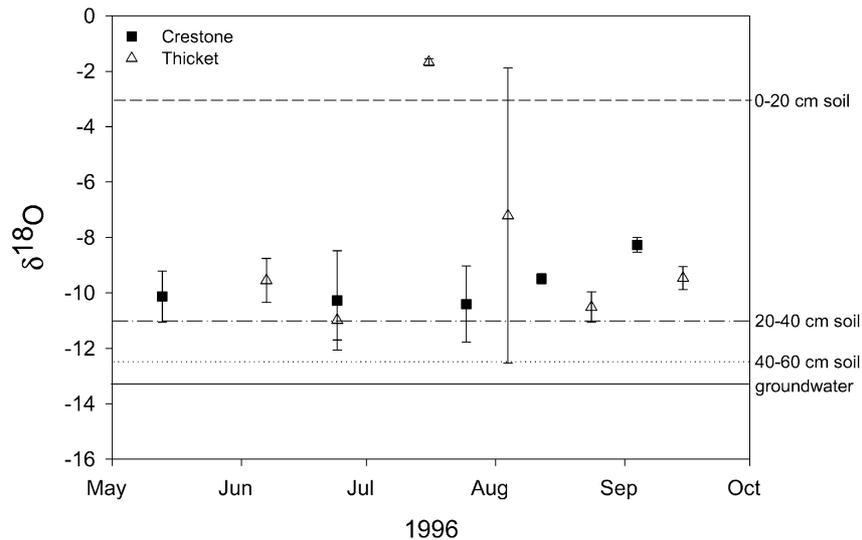


Figure 5. Mean ( $\pm 1$  se)  $\delta^{18}\text{O}$  (‰) for *Chrysothamnus nauseosus* during 1996 for sites with groundwater 2 m or less.

shallow water tables were recharged by both precipitation and capillary water, while soils at similar depths at sites with deeper water tables, are recharged solely by precipitation.

#### Influence of water table and precipitation

Water table depth influenced water sources used by native shrubs in our study sites. On sites with a water table  $< 2$  m deep, *S. vermiculatus* and *C. nauseosus* had  $\delta^{18}\text{O}$  signatures that changed little during the summer, and these species appear to be primarily using water from the upper 0.5 m of soil, which was recharged by both precipitation and capillary rise. On sites with a water table greater than 2 m deep water acquisition patterns varied by species. The  $\delta^{18}\text{O}$  of *C. greenei* xylem water indicated that it acquired only water from shallow soil layers recharged by precipitation. In 1996, both *S. vermiculatus* and *C. nauseosus* used a mixture of deep soil water and groundwater, with little difference in  $\delta^{18}\text{O}$  during the summer. In the pre-monsoon period in 1997, both species utilized predominantly deep soil water and groundwater; however their isotopic signatures indicate that both species switched to use precipitation recharged soil water during the 1997 monsoon season.

The sources of water utilized by *S. vermiculatus* have not been previously studied, even though it is one of the most common and widespread shrubs in the western U.S. and a known phreatophyte (Mozingo, 1987). Several researchers have previously sugges-

ted that in the Great Basin Desert *C. nauseosus* does not acquire soil water recharged by summer rain (Donovan and Ehleringer, 1994; Ehleringer et al., 1991; Flanagan et al., 1992; Flanagan and Ehleringer, 1991; Toft, 1995). However, our data suggests that this species can switch from utilizing primarily groundwater or deep soil water to rain recharged soil water during the summer. Climate differences, particularly long-term trends in the seasonal pattern of precipitation, may explain differences in *C. nauseosus* water acquisition patterns in the Great Basin vs. San Luis Valley. The Great Basin Desert has a winter dominated precipitation regime with summer rains being episodic and of low volume. Donovan and Ehleringer (1994) suggested that *C. nauseosus* was adapted to utilize only dependable deep soil water recharged by winter and early spring precipitation, and Ehleringer et al. (1991) and Flanagan and Ehleringer (1991) found that *C. nauseosus* in the Great Basin has a well-developed deep root system with few shallow roots. The San Luis Valley has nearly the opposite precipitation pattern, with dry winters and  $\sim 70\%$  of the annual precipitation falling between May and September and  $\sim 50\%$  falling in the monsoon season from July through September. It is likely that both *S. vermiculatus* and *C. nauseosus* in the San Luis Valley are adapted to utilize predictable summer precipitation. Differences may also be due to differences in genetic races of *C. nauseosus*. We investigated *Chrysothamnus nauseosus* ssp. *consimilis*, the only subspecies of *C. nauseosus* occurring in our study area, while

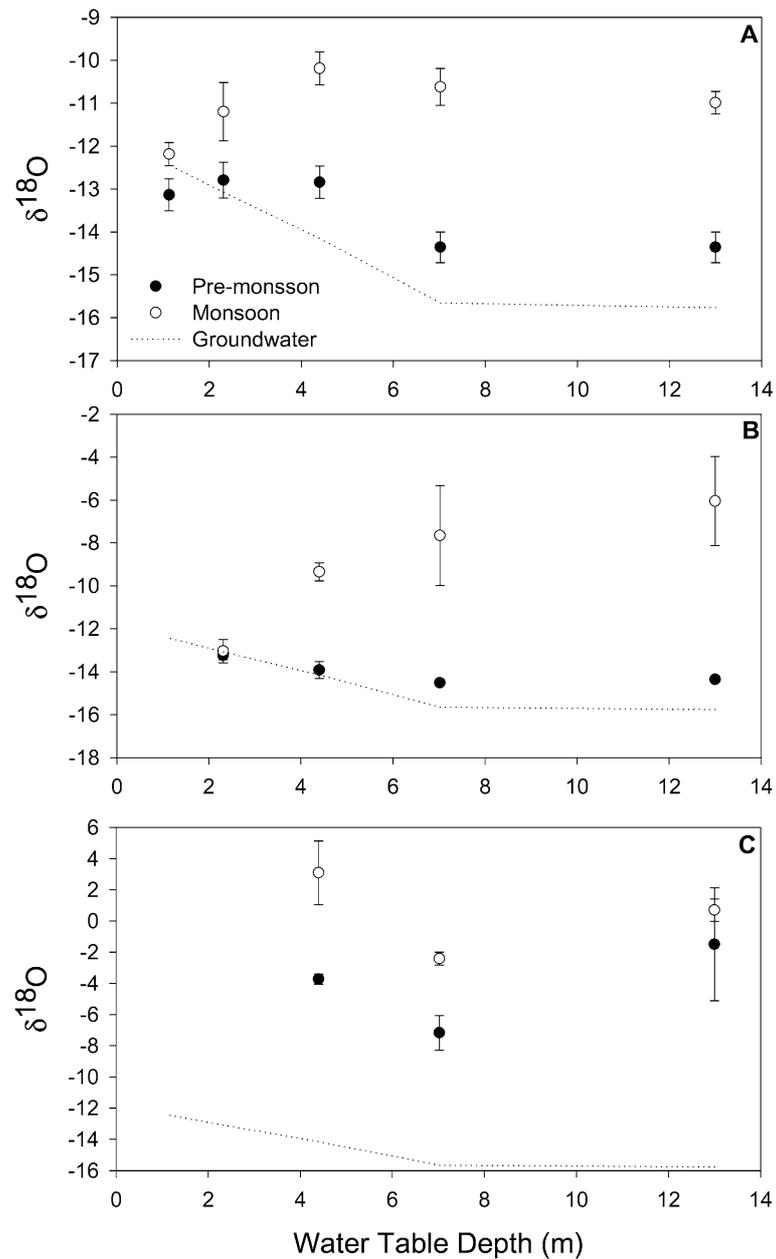


Figure 6. Mean ( $\pm 1$  se)  $\delta^{18}\text{O}$  (‰) for groundwater and (A) *Sarcobatus vermiculatus*, (B) *Chrysothamnus nauseosus*, and (C) *Chrysothamnus Greenei* on 27 June 1997 (pre-monsoon) and 13 August 1997 (monsoon).

other researchers have not specified the taxon in their study areas. However, numerous geographically and ecologically isolated races/subspecies of *C. nauseosus* occur in the Great Basin (Welsh et al., 1987) and distinctive water acquisition patterns may occur among taxa.

Our results are consistent with the conceptual model developed by Ehleringer and Dawson (1992), which suggested that plants utilize more summer rain as the percentage of summer rain increases. Plants may also develop dimorphic root systems in regions with greater summer rain, which allow them to utilize both deep water and summer precipitation recharged

shallow soil water. Root profiles for both *S. vermiculatus* and *C. n. consimilis* at 17 sites investigated in the San Luis Valley with water tables from 0.3 m to 4.4 m were strongly dimorphic (Cooper and Chimner, unpublished data), with woody roots reaching to near the water table at least 4 m deep, but also a very well developed lateral root system with ~70% of the fine root biomass occurring in the upper 40 cm of soil. We are unsure how deep *S. vermiculatus* can root in the San Luis Valley, but Meinzer (1927) documented roots 6 to 17 m below the soil surface. We have seen *S. vermiculatus* roots reaching the water table at ~4.5 m depth in a backhoe excavated trench. However, our Greasewood site had a water table ~13 m deep and xylem water from *S. vermiculatus* at this site was isotopically similar to *S. vermiculatus* on our other sites with water tables ranging from 2–13 m deep. Although vertical root profiles may not indicate how much water is removed from each soil strata (Schwinning and Ehleringer, 2001), they do suggest that San Luis Valley plants have roots in locations where they can utilize both shallow soil water and deep groundwater.

Similar patterns of summer water usage have been reported for other woody plants in the southwestern US. For example, the utilization of summer precipitation by *Pinus edulis* and *Juniperus osteosperma* was controlled by the percent of annual precipitation that fell in summer (Williams and Ehleringer, 2000). Dawson and Pate (1996) found that *Banksia grandis*, *Eucalyptus globulus*, and *E. camaldulensis* in western Australia acquired up to 47% of their water from the water table via a deep taproot during the dry season, but acquired mostly soil water recharged by precipitation through lateral roots in the wet season. Another Australian study found that *E. camaldulensis* acquired primarily groundwater during the dry summer, but switched to primarily rain recharged soil water in winter (Mensforth et al., 1994). Other desert shrubs including *Artemisia tridentata*, *Chrysothamnus viscidiflorus*, and *Gutierrezia sarothrae* have been shown to acquire water from summer rains indicating that they had active root systems in shallow soil horizons (BassiriRad et al., 1999; Ehleringer et al., 1991; Flanagan et al., 1992; Schwinning et al., 2002).

Our results indicate that the non-phreatophytic shrub *Chrysothamnus greenei* used only soil water, while the phreatophytic shrubs *Sarcobatus vermiculatus* and *Chrysothamnus nauseosus* utilized both soil water and groundwater. This is the first reported documentation that these phreatophytic shrubs utilize summer precipitation. We suggest that these species

are well adapted to use the consistent summer precipitation that occurs in the San Luis Valley, and an appreciable proportion of the water utilized in evapotranspiration each year is from precipitation recharged soil horizons.

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