

SHORT-TERM RESPONSES OF CLEAR CUTTING ON THE WATER SUPPLIES,  
WATER STATUS AND GROWTH OF REMAINING VEGETATION: WHICH  
SPECIES HAVE THE MOST TO GAIN?

THESIS

Presented to the Graduate Council  
of Texas State University-San Marcos  
in Partial Fulfillment  
of the Requirements

for the Degree

Master of SCIENCE

by

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San Marcos, Texas  
December 2010

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## **ACKNOWLEDGEMENTS**

First and foremost I would like to thank my husband, Nathan, whose moral support and clear headed reasoning helped me to stay sane during the trials of grad school. I would also like to thank my parents, Tony and Laurie Cardella, for their ongoing support and encouragement throughout the years. My advisor, Susan Schwinning, deserves a huge thank you, for all of her help and guidance throughout my graduate studies. I would also like to acknowledge my committee members, Benjamin Schwartz and Georgianne Moore, for their help and expertise. Kelly Goodsheller also deserves a thank you for all her help in the lab and all those predawn trips to Camp Bullis. I would also like to acknowledge Lucas and Chris and the other employees out at Camp Bullis Military Base for allowing access to the field site, as well as the folks from Zara environmental for their integral part in this project. Last but not least, I would like to acknowledge everyone in the Schwinning Lab and those who helped with fieldwork. This project was funded by the Norman P. Hackman ARP grant.

This document was submitted on November 17, 2010.

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Over the past century and a half, central Texas grasslands and savannahs have experienced widespread woody plant encroachment of Ashe juniper (*Juniperus ashei*). This has had negative impacts on grassland productivity, habitat variety and, many believe, aquifer recharge. As the first phase of a longer-term study, short-term effects of juniper removal on ecosystem water availability were examined to improve the understanding of the ecohydrologic effects of this management practice. The study was conducted at Camp Bullis Military Base near San Antonio. In 2008, 90.6 % of all juniper trees were removed from a 2730 m<sup>2</sup> area on a wooded hill slope. The area was characterized by shallow soils (0-.3 m) overlying fractured bedrock, typical for the karst terrain of this area. For the first two years after clear-cutting, soil water content, predawn water potentials, sap flow rates, and sap water stable isotope ratios of live oak (*Quercus fusiformis*) and Ashe juniper trees were monitored and compared with those in an adjacent, unaltered oak-juniper woodland. Soil water content in the cleared area was consistently higher than in the woodland, though differences between sites declined in 2010. During the exceptional summer drought of 2009, predawn water potentials of trees

in both sites declined, but woodland trees reached lower potentials and their sap flow rates declined more rapidly, suggesting a faster depletion of stored water. In 2010, precipitation levels were at or above average for most of the year and there was little difference in water potentials and sap flow rates between sites. Sap water stable isotope ratios of trees in the woodland and the clearing were evaporatively enriched and distinct from the stable isotope ratios of cave drips, indicating shallow water sources for trees at both sites. These results suggest that clear-cutting reduced evapotranspiration (ET) and lead to an increase in ecosystem water storage in the two years after clear-cutting. However, ET savings may be limited by the relatively low capacity and shallow location of water storage in the root zone of trees.

## CHAPTER I

### SHORT-TERM RESPONSES OF CLEAR CUTTING ON THE WATER SUPPLIES, WATER STATUS AND GROWTH OF REMAINING VEGETATION: WHICH SPECIES HAVE THE MOST TO GAIN?

#### INTRODUCTION

Over the last century, semi-arid grasslands and savannahs worldwide have undergone an increase in woody vegetation (Archer et al. 1988, Van Auken 2000). Tree and brush encroachment has been attributed to many potential drivers, including climate change, heavy grazing by livestock and the subsequent reduction in fine fuels and fire frequency (Van Auken 2000). As woody plant cover increases, ecosystems often show signs of degradation in terms of reduced rangeland productivity and biodiversity (Schlesinger et al. 1990, Hibbard et al. 2001) and increases in erosion (Grover and Musick 1990). Encroachment of woody plants can also affect an ecosystem's hydrological cycle by increasing evapotranspiration rates, thus potentially decreasing ground water recharge (Huxman et al. 2005, Seyfried and Wilcox 2006).

The relationship between evapotranspiration (ET) and recharge is evident from the water budget equation (e.g. Huxman et al. 2005):

$$P = ET + R + S \quad \text{eq 1}$$

where P = annual precipitation, R = annual runoff, S = annual deep groundwater recharge below the root zone of plants and ET = total annual evapotranspiration. Vegetation

change from grassland to woodland is thought to increase ET through a number of mechanisms: a) more precipitation is intercepted by trees and evaporates before entering the ground, and b) transpiration is increased as a consequence of changing the local energy balance (greater absorption of net radiation, increased turbulence), c) transpiration is increased through the greater rooting depth of trees, which makes more stored water available for uptake (Jackson et al. 2005, Huxman et al. 2005, Seyfried and Wilcox 2006). The water balance equation demands that if ET increases, R and/or S must decrease, negatively effecting stream flow (through R) and groundwater levels (through S).

However, how much greater the ET of woodlands is compared to grasslands, is a matter of ongoing debate and depends greatly on climate regime (Bosch and Hewlett 1982, Wilcox 2002), landscape settings (Sala et al. 1996), and geologic constraints (Seyfried and Wilcox 2006).

It is well established that in humid climates, where P exceeds potential evapotranspiration (PET), increases in forest cover generally lead to decreases in water yield (Bosch and Hewlett 1982, Trimble et al. 1987). Conversely, removal of forest/woody plant cover in these areas has been connected to increases in water yield (Zhang 2001). In wet regions, vegetation effects on the local energy balance are largely responsible for this effect.

By contrast, in arid climates, where PET exceeds P by a large margin, changes in woody plant cover have little effect on water yield, since ET trends towards P are independent of plant cover type (Wilcox 2002, Wilcox et al. 2003). However, in semiarid areas, where precipitation and potential evapotranspiration are similar in

magnitude ( $PET \approx P$ ), the link between woody plant cover and water yield is more complex, less well understood, and may depend more on seasonality of rainfall, local landscape and geologic conditions (Wilcox 2002).

In semiarid Mediterranean climates, where the majority of precipitation falls during the winter (such as the chaparral communities), woody plant removal has been shown to increase water yield (Zang 2001). The likely reason is that during the warm season ET is fed from water stored in deep soil layers that trees can access but grasses cannot. In semiarid areas where precipitation coincides with the growing season, other factors besides climate, such as geology, play a larger role on how woody plants affect the hydraulic regime of an area (Huxman 2005). If an area has deep soils, trees can access all water entering the soil and ET would be higher and close to P. If, however, soils are shallow and restricting rooting depth, water can infiltrate below the root zone of trees and more P would go towards S. In such regions, differences in the rooting depth of trees and grasses are reduced, leading to smaller differences in the impact of vegetation change on water yield.

One geological setting for which the relationship between woody cover and hydrology remains controversial are karstic landforms (Wilcox 2002, Wilcox et al. 2005, Wilcox et al. 2006, Tennesen 2008). Karst is a hydrologically complex terrain characterized by sinkholes, caves, sinking streams and springs and often has little soil cover.

Hydrologic models applied to the karst terrain of the Edwards Plateau, Texas, USA predict anywhere from a 100% increase in water yield from brush removal (Wu et

al. 2001), to 31.95 – 160.9 mm/yr increases in water yield or 1-47% increases in annual runoff (Bednarz et al. 2000, Brown and Raines 2002, Afinowicz 2005).

However, field studies have generally failed to corroborate predictions of significant water savings through brush removal (Wilcox 2002). Only a handful of field studies have been conducted on this subject and they tended to be on a small scale both spatially and temporally. A study conducted by Thurow and Huster (1997) showed an increase of 94 mm/yr in groundwater recharge after juniper removal. Huang (2006) found small scale water savings of 46 mm/yr on rangelands with active or historically active springs. Wilcox et al.'s (2005) study in watersheds without springs found that brush removal had little to no influence on stream flow, and Dugas et al. (1998) found decrease in evapotranspiration rates that lasted 2 years and lead to a slight increase in water savings (40mm/yr) after which, vegetation water use recovered to pretreatment levels.

Dugas et al.'s (1998) study in particular highlights that the successional dynamics of clear-cut areas are also quite important for predicting water savings over longer time scales. If woody plants re-establish quickly through accelerated growth of remaining seedlings and juveniles (Owens and Schlesing 1995, Moore and Owens 2006), as well as re-sprouting (Urkert et al. 2001), then brush removal will have only minor, transient effects over the course of several years. Furthermore, if the original woody vegetation was fairly shallow-rooted, then seedlings and saplings would regain pre-treatment rooting depths relatively quickly, thus shortening the transition to pre-treatment evapotranspiration rates. Conversely, if the original vegetation was deep-rooted,

recovery might take decades and the cumulative water savings due to clear-cutting could be substantial.

Clearly, hydrological models, and the accuracy of their predictions concerning the effects of brush removal on water yield, would greatly benefit from a better understanding of the rooting patterns and water use of trees in karst terrains. Karst is a hydrologically complex landscape formed by the dissolution of soluble rock, often carbonate rock, where mildly acidic flowing water has solutionally enlarged openings to form a subsurface drainage system (Bonacci 2009). Beneath a usually rocky and thin soil cover lies a layer of highly fractured and weathered limestone called epikarst. This is a transition zone between the soil and the unweathered bedrock that can be several to 15 m thick (Klimchouk 2004). The epikarst regulates infiltration and groundwater recharge via multiple pathways, which range from slow flow through micropores to quick flow through open shafts (Klimchouk 2004, Bonacci et al. 2008). It is unclear to which components of epikarst water trees are connected, which ultimately governs their effects on recharge flows: if trees tap into relatively shallow sources of water residing in narrow fissures and soil lenses, and perhaps in the rock itself (Rose et al. 2003), tree cover may have little impact on recharge flows. Conversely, if trees tap into deeper, perched water tables that regularly overflow and drain into an aquifer, then water uptake by trees could substantially reduce recharge flows.

Jackson et al. (1999) did find evidence for the latter case, in a study in the eastern edge of the Edwards Plateau, Texas, USA, where tree roots were found in caves accessing free-flowing water. Deep roots in Ashe juniper (*Juniperus ashei*) and other species had a high capacity for water uptake from these sources, based on the anatomy of

xylem vessels (which were wider in deeper roots; McElrone et al. 2004). In escarpment live oak (*Quercus fusiformis*) water uptake was enhanced by aquaporins (water-specific protein channels found in membranes; McElrone et al. 2007). However, other studies since then (Schwinning 2008, Litvak et al. 2010) found evidence to the contrary, showing that trees on the eastern Edwards Plateau become drought stressed quite rapidly and regularly, and do not exhibit an ability to switch to persistent, deeper water sources in times of drought.

In this study, we took the approach of following the immediate hydrological consequences of brush removal on the water relations of the remaining trees a) to determine the magnitude of change in water availability in the soil/epikarst system, and b) to determine which species profit the most from increases in water availability, to anticipate successional responses. To accomplish the first goal, soil water content and the water status of oak and juniper trees left standing in a recently clear-cut area was compared with values obtained in an adjacent unaltered forest. To accomplish the second goal, sap flow rates of oak and juniper trees were determined and compared across sites. Additionally, cover changes in the first two years after clear cutting were documented, as well as the growth rates of common woody species in the over-and understory.

The study was part of a larger research effort that also involved monitoring cave drip rates (the study site is located above a shallow cave) for several years before and after clear cutting. Cave drips indicate the rate of drainage out of the epikarst and can be interpreted as a proxy for local groundwater recharge. The in-cave study, in combination with the research activities described here, provides a fairly comprehensive, if local,

hydrological analysis of brush control that adds to the limited data available for the Edwards Plateau region.

## METHODS

### *Study area*

The Edwards Plateau is an uplifted limestone plateau in a semiarid to sub-humid climate zone located in southwest central Texas, USA (Larkin and Bomer 1983). At its lowest elevation along its southeastern edge, it is dominated by shallow soils overlying and filling solution enhanced fractures and bedrock. For the last 150 years, the region has been encroached predominantly by Ashe juniper (*Juniperus ashei*) (Archer 1994, Owens and Schlesing 1995).

The study was conducted at Camp Bullis Military Base (29°37'26.21"N, 98°34'14.86"W), 24.5 km NNW of San Antonio, TX. Camp Bullis is located on the Balcones Escarpment on the southeastern edge of the Edward's Plateau. The study site exemplifies the dominant landform of this area, including shallow rocky soils with mixed live oak (*Quercus fusiformis*) and Ashe juniper woodlands and dispersed grassy patches. Common understory species include Texas persimmon (*Diospyros texana*) and agarita (*Berberis trifoliolata*). The average annual precipitation is 836 mm. Average monthly temperatures range from a low of 4.05°C in January to a high of 34.8°C in August (NOAA Online Weather Data).

The study took place at two sites on a sloping hillside; an area of 2730 m<sup>2</sup> that was cleared of most juniper trees and understory shrubs in September 2008 and an adjacent area of intact forest, about 30 m NE and uphill from the clearing, which was

used as a control site (Figure 1). The cleared area overlies a shallow cave, about 10 m below. The sites are on the lower portion of the Edwards formation, with contact between it and the underlying Glen Rose formation being exposed in the shallow cave.

A weather station was installed at the site on 11/4/2004, by Camp Bullis contractor, Zara Environmental, 4 years before juniper removal giving us pre and post treatment weather data. Measurements of rainfall and temperature were continuously monitored and recorded at 15 minute intervals by a Campbell Scientific datalogger (Campbell Scientific, Logan, UT, USA).

#### *Site comparison and vegetation changes*

Site characteristics including woody plant density, vegetation and ground cover were determined for the entire cleared area (2730 m<sup>2</sup>) and for a representative 720 m<sup>2</sup> area in the forest. In June 2009 both sites were divided into continuous 2 m wide belt transects, which, in the case of the clearing, covered the entire area. In the forest, 12 belt transects of 30 m length were censused. Along the belt transects, the basal diameter of woody plants greater than 25 mm were recorded by species and location, stems less than 25 mm in diameter were tallied for each 0.5 x 2 m element of the belt transect. Stumps of felled trees were recorded in the same way, to estimate forest stem density before clearing. The belt transect data were used to calculate the total density of the woody plants by dividing the stem count – by species – by the total area censused (Bonham 1989).

In June 2009 and 2010, at both the forested and cleared site, canopy and ground cover along the boundary lines of each belt transect were measured using the line

intercept technique (Bonham 1989). The canopies of all woody plants intercepting the line were recorded by species, height of cover, and the start and end points of the intercept. Other species were assessed only in terms of cover class and categorized as either grass or forb, along with other cover categories, including bare soil, woody debris (any branches over 25 mm in diameter), gravel, rock, bedrock, and litter. Any canopy or ground cover type of 5 cm or less in intercept length was ignored, as well as any gap in a single cover type of 10 cm or less. The line intercept data was used to estimate percent cover for the various cover classes, assuming that % intercept length corresponds to % area cover (Bonham 1989).

#### *Growth of understory shrubs and overstory saplings*

The heights and length of tagged branches of dominant understory species and overstory species saplings were measured in June of 2009 and 2010. The species selected for this study were Ashe juniper, Texas persimmon (*Diospyros texana*), agarita (*Berberis trifoliolata*) and live oak, for which root sprouts were measured since seedlings are extremely rare in this species (Russell and Fowler 1999). Six immature individuals of each species were selected in both the clearing and the forest, equaling 48 plants total. Individuals were selected using the following criteria: plants had to be actively growing with intact apical buds, multiple branches with multiple leaves, diameter <1.5 cm and a height less than or equal to 1m. Three branches on each individual were tagged with loosely wrapped wire so that the same branches could be identified and measured again a year later. The tagged branches were selected at random, but they had to be terminal with

multiple leaves. To determine the effect of clear-cutting on growth, the annual change in height and branch length was compared between sites, using univariate ANOVA.

#### *Soil moisture*

Volumetric soil moisture was monitored continuously by four ECH<sub>2</sub>O EC-5 soil moisture sensors (Decagon Devices, Pullman, WA, USA) in both the cleared and forested sites. Soil moisture probes were installed on May 5, 2009 for the cleared area and May 24, 2009 for the forested area a few centimeters above bedrock at a depth of about 20 cm. Soil moisture was monitored continuously on 60 second intervals and recorded as 15 min averages on a Campbell Scientific datalogger. Effects of time and site on soil moisture were tested by repeated measures ANOVA on consecutive five day averages.

#### *Mature tree water relations*

To follow plant water status, water use, and water source, of mature trees in the forest and the clearing, six mature Ashe juniper and live oak trees were selected for monitoring.

To determine plant water status, predawn water potentials were taken monthly using a Scholander pressure bomb (PMS Instrument Co., Model 1000, Albany, OR, USA). In general, water potentials taken before dawn reflect the water availability integrated over the active root zone of an individual plant. Differences over time, between sites and species were analyzed using repeated measures ANOVA.

To characterize water sources, stems were sampled for the measurement of the stable isotope ratios of hydrogen and oxygen in stem water. There is no isotope

discrimination associated with the transport of water from soil to root or along the xylem transport pathway, thus water extracted from suberized plant stems has the same isotope ratio as water extracted from the plant's root zone and can be used to trace and distinguish plant water sources (Ehleringer and Dawson 1992).

Stem samples for the measurement of stem water stable isotope ratios were collected monthly on the same day as predawn water potentials. Plant stem samples were taken from small branches upstream of any foliage, since leaves are sites of evaporative enrichment and it is possible for enriched water to diffuse backwards into the xylem, especially if transpiration rates are low. Taking samples well below evaporation sites minimizes this source of error. Stem samples were placed in glass vials, capped immediately, sealed with parafilm and frozen until extraction. Stem water was extracted using cryogenic vacuum distillation following the method described by Ehleringer (2000). The extracted water was analyzed on a liquid water isotope analyzer (Los Gatos Research, Inc., Mountain View, CA, USA).

In addition to sampling the stable isotope ratios of hydrogen and oxygen of stem water, rain water and cave drip water were also regularly sampled to allow for comparisons of stem water samples with environmental water sources where they were easily obtainable.

Stable isotope ratios of hydrogen and oxygen are presented in delta notation:

$$\delta = (R_{\text{sample}}/R_{\text{standard}} - 1) * 1000\text{‰} \quad \text{eq. 2}$$

where  $R_{\text{sample}}$  and  $R_{\text{standard}}$  represents the molar ratio of D/H for  $\delta\text{D}$  or  $\text{O}^{18}/\text{O}^{16}$  for  $\delta^{18}\text{O}$  of the sample and a water standard, Vienna Standard Mean Ocean Water (V-SMOW), respectively (Ehleringer and Dawson 1992). Differences in stable isotope ratios due to

time and species were analyzed by repeated measures ANOVA. We did not compare isotope ratios between sites, since we could not assume that soil and epikast water sources exhibited the same patterns of enrichment.

The rate of water uptake in trees was monitored for two years by measuring sap flow rates, using the heat dissipation method described by Granier (1987). Each instrumented tree has a reference and a heated sensor (each containing a copper-constantan thermocouple) installed on its north facing side about 1.0 - 1.5 m above the ground or as high as possible below the lowest branch. The sensors were placed in line with the direction of the transpiration stream and 10 cm apart with the heated sensor on top. The heated sensors were wrapped in a coil of constantan wire that produced a constant heat source when supplied with a continuous current of 105-125 mA. According to Granier, the temperature difference between these two probes varies with sap flow rates,  $u$  ( $m d^{-1}$ ):

$$u = 119 \times 10^{-6} K^{1.231} \quad \text{eq. 3}$$

where  $K = (\Delta T_{\text{Max}} - \Delta T) / \Delta T \quad \text{eq. 4}$

The term  $\Delta T_{\text{Max}}$  (in °C) refers to the maximum temperature difference measured between the heated and the reference probes during predawn conditions, when sap flow is zero and the temperature difference is maximal,  $\Delta T$  refers to their temperature difference at all other times, when the rising sap accelerates heat dissipation and lowers the temperature difference. Sap flow rates were integrated over the course of a day and reported as daily rates in  $m d^{-1}$ .

The temperature difference  $\Delta T$  was measured directly by wiring the two thermocouples in series and connecting the remaining leads to a Campbell Scientific AM16/32b multiplexer, which was in turn controlled by a CR1000 Campbell Scientific datalogger (Campbell Scientific, Logan, UT, USA). Thermocouple voltage was measured every 60 seconds and the 15 min average was recorded. Two sap flow stations, one in the forest and one in the clearing, were each powered by two 125 Watt solar panels (BP, Houston, TX).

On February 19, 2010, the two-sensor design described above was replaced with a four-sensor design as described in Goulden and Field (1994). This involved adding 2 reference sensor probes approximately 10 cm parallel to the heated and reference sensors of the original set up. This modification was expected to reduce artifacts due to temperature gradients along the stem not associated with the heated probe but arising naturally.

Calculated sap flow velocities were then used to calculate total sap flow  $F$  ( $\text{m}^3 \text{d}^{-1}$ ) per tree using the following equation:

$$F = u S_A \quad \text{eq. 5}$$

where  $S_A$  is the active sapwood area ( $\text{m}^2$ ).  $S_A$  of juniper trees were calculated using the basal diameter of trees ( $D$ ) measured while surveying woody plant density using the following equation (Keith Owens, unpublished data):

$$S_A = 0.672 D^{1.7409} \quad \text{eq.6}$$

Due to limited information on active sapflow area of live oak, two boundary estimates of potential sapwood areas, a high estimate ( $S_A = 50\%$  of total stem area) and a lower estimate ( $S_A = 10\%$  of total stem area) were used to set a range of potential

transpiration rates for the two oak populations. Total oak and juniper transpiration per site were calculated by summing the total  $S_A$  for each species at each site and dividing it by the area surveyed. This was then multiplied by the average value of  $u$  for each species.

The effects of time, site and species on sap flow velocities were analyzed using repeated measures ANOVA on five day averages of daily sap flow rates. Time periods before and after the change in instrumentation were analyzed separately.

#### *In-cave measurements*

Inside the cave, directly underneath the clearing, air temperature, drip rates from speleothems and drip water chemistry (temperature, specific conductance) were collected in 15 min intervals since 2004. Cave drip water samples were collected on a semi monthly basis or when drips were present between 2008 and 2010 to determine the stable isotope ratio of the drip waters. Drip rates at 3 drip sites were collected for ~4 years prior to the clear-cutting over the cave site using ~1L homemade tipping buckets and were recorded at 15 minute intervals to a data logger.

#### *Statistical analyses*

For the repeated measures analyses, Mauchly's test (Mauchly 1940) was used to test the assumption of sphericity, and was usually rejected; therefore lower bound p values are reported. Univariate ANOVAs were used to test for species and site effects on monthly predawn and stable isotope data. All statistical analyses were done using PASW Statistics 18, (SPSS Inc., Chicago, IL).

## RESULTS

### *Site characteristics and vegetation manipulation*

Before clearing, Ashe juniper was the most common mature tree (with diameter > 65 mm), followed by live oak and persimmon (Table 1). This species abundance ranking was the same as in the reference forest site, although there were some differences:

Before clearing, the site had higher juniper density and lower density of all other species compared to the forest site. Overall density of stems > 65 mm diameter was larger by 17% compared to the forest site.

After juniper clearing, the most common mature tree was live oak followed by juniper and persimmon. Clearing reduced the density of stems > 65 mm diameter by 71% and stem density of plants 25-65 mm in diameter by 62%. The greatest reduction in stem density (90%) occurred in the target species, juniper. There was little reduction in sapling density (diameters < 25 mm) due to juniper removal, and sapling density both before and after clearing was lower than in the forest.

### *Water relations in 2009*

During 2008 and up until September 2009, with the exception of March 2009, rainfall was below average. This produced chronic drought conditions that intensified in the summer of 2009 (Fig. 2, 3a). Soil moisture at 20 cm declined from May to the end of August, then increased and remained high from September to the end of the 2009 (Fig. 3b). The same trend was seen in the forest and in the clearing, although volumetric water content was consistently higher in the clearing. There was no significant time \* site interaction (Table 2), as attested by the two site's similar responses to rainfall events.

Similarly, the predawn water potentials of the instrumented trees changed significantly over time, and there were significant effects of site and species, each interacting with time, but no site x species interactions (Fig. 3c, Table 2). Overall, predawn water potentials were consistently higher at the cleared site and consistently higher for oak, and these differences increased as the summer drought progressed.

Analysis of sap flow velocities indicated significant effects of time and site, but no interactions with time, or between site and species (Fig. 3d, Table 2). Essentially, sap flow velocities began to decline in June, but the decline was more gradual for the two species in the clearing. By the end of June, sap flow rates of trees in the forest were below 0.5 m/day, and after responding to an isolated rainfall event in July, sap flow velocity dropped to near zero and stayed there until September. By contrast, sap flow velocities of trees in the clearing only dropped below 0.5 m/day at the end of August.

With the onset of rains in September, sap flow velocities picked up again, but they remained below maximal values measured in late spring. For this period, significant differences were found between sites and species sap flow velocities (Table 2), with oak trees having generally higher velocities than juniper trees, and trees in the clearing having higher velocities than forest trees. Thus, despite of the large rainfall input in September and October (Fig. 1), site differences that established during the drought were maintained in fall and winter.

Estimated total transpiration of oak and juniper at each site reveal that for three months during the driest part of the summer tree water use at the stand-level was very similar between sites (Fig. 4). As rainfall increased in mid- September, transpiration rates in the forest increased creating a difference of 1 mm per day or less in water use

between the two sites which lasted until late December, when cold temperatures reduced evaporation potential at both sites.

At both sites, stable isotope ratios of stem water changed significantly over the study period and there were species x time interactions, although they were significant only in the  $\delta D$  values (Fig. 5, Table 3).

In the forest until and including the June sampling date, the species had indistinguishable stable isotope ratios of stem water, however, for July and August the stem water of oak was less enriched than that of juniper. The isotope ratios of both species increase from July to September, suggesting the gradual evaporative enrichment of their water sources. After the drought- breaking rain fall event in September 2009, isotope ratios for both species dropped sharply as new rainwater entered the soil/epikarst system and was taken up by plant roots. However, at the September sampling date, 8 days after the drought-breaking rainfall event, juniper had a less enriched isotope ratio, suggesting a greater proportion of new rain water in juniper stems.

In the clearing, species show no large difference in stem water isotope ratios until the very end of the summer drought in early September. By this time (and also once before in July), juniper had the more enriched stem water than oak, as in the forest. However, unlike in the forest, there was no trend of increasing enrichment over time in oak stem water. After the drought breaking rain event in mid September the water sources of both species became less enriched, and although oak's stem water remained significantly more enriched compared to juniper's, the difference was much smaller than in the forest.

### *Vegetation cover changes 2009-2010*

In May 2009, the forest site had 89% overstory cover as compared to 15% in the clearing (Table 4). The species with by far the greatest cover in the clearing was live oak (14%). The most abundant species in the forest were juniper and live oak, covering 60% and 48% of the area, respectively.

Ground cover for both sites was dominated by litter (clearing = 72%, forest = 85%; Table 5). The clearing's second most common cover was gravel (13%) and rock (12%) was second in the forest.

From May 2009 to May 2010, forest vegetation cover changed little, with the exception of a 6% decline in juniper cover and a 4% increase in oak cover (Table 4, Fig. 6). By contrast, woody plant cover changed little in the clearing, but there was a 16% increase in herbaceous plant cover (grasses, forbs and sedges).

### *Growth of tagged saplings 2009 - 2010*

Species tagged in 2009 had all increased in height and, with the exception of juniper had increased total branch length by 2010 (Table 6, Fig. 7). However, the only species showing a significant site effect on growth was agarita, indicating that it had higher rates of branch growth in the clearing.

### *Water relations in 2010*

Precipitation was at or above average for much of 2010 except for June and August (Fig. 2). As in the year before, soil moisture declined from May to September, but there were more frequent interruptions in the downward trend through rainfall inputs

(Fig. 3b). Site differences in soil moisture remained significant (Table 2), but appeared to diminish during the summer, chiefly through an increase in the forest soil moisture compared to the previous year, rather than a decrease in soil moisture in the clearing.

For the predawn water potentials, effects of date, site and species were significant as in the previous year (Table 2). Predawn water potentials remained high until July (Fig. 3c) and began to drop only in June. They reached their lowest values in August, as in the year before, although the values were far above the 2009 minima. In July and August, juniper trees at both sites had the lowest water potentials, while those of the oak trees remained high throughout. Paradoxically, and in contrast to the year before, juniper trees in the clearing had lower water potentials than juniper trees in the forest. Large rainfall events in September 2010 allowed water potentials to recover, removing any significant differences between sites and species.

As temperatures began to increase in March, around the time that the sap flow sensor system was upgraded, sap flow velocities also increased. High day-to-day variability in velocities was presumably due to frequent cloud cover changes and rainfall events (Fig. 3a). However, sap flow velocities did not differ significantly between sites or species in 2010 (Table 2).

With the sap flow velocities nearly equal between sites, estimated total oak and juniper transpiration rates are dominated by differences in the tree densities between sites (Fig. 4). During the summer months when transpiration rates were highest, the forest had roughly a five fold higher total tree transpiration rate than the clearing (Fig. 4b and c).

*Comparison of precipitation, cave drip and stem water isotope ratios*

Precipitation samples were scattered along the global meteoric water line (GMWL; Fig. 8). All cave drip collections were on or above the GMWL, indicating that some drip collections, especially during summer, may have been condensate rather than drainage out of the epikarst. Importantly, all water extracted from stems fell below the GMWL, indicating the evaporative enrichment of the water sources used by oak and juniper.

## DISCUSSION

In this study, the ecohydrologic consequences of juniper removal from a hill slope on the eastern Edwards Plateau were examined to quantify the change in water availability in the soil and the root zone of trees left standing, and to determine which species gained the most from the removal. To do so, soil moisture, vegetation changes and the water relations of trees left standing in a cleared site were compared with those in an adjacent forest. Even though these methods addressed the question of water savings through clear-cutting only indirectly, the study contributed a more sophisticated understanding of water use limitations in the Texas Hill Country and the potential effectiveness of clear-cutting as a tool to limit plant water use.

### *Changes in water availability to trees*

As expected, the drastic reduction of woody cover, from about 90% to 15% through the removal of 89% of all juniper trees, changed the water budget at the cleared site, presumably through reductions in evapotranspiration (ET). Although ET was not measured directly, decreases in the rate of water loss from the soil and epikarst were

observed during the summer, especially in 2009. Decreases in the rate of soil water loss were observed directly (Fig. 3b), while decreases in the rate of loss from the epikarst were inferred from the rate of decline in the predawn water potentials of trees (Fig. 3c).

There were substantial differences in the weather patterns that governed the first two growing seasons after the vegetation manipulation: 2009 was a dry year, following an even drier year, with record drought conditions emerging by the end of summer (US Drought Monitor). The second year of this study was, by contrast, quite wet, with rainfall at or above average from September 2009 to May 2010 (Fig. 2). We can derive different insights on the effects of clear-cutting by examining what happened in the respective years.

The summer of 2009 tested the limits of water storage at the site. Both oak and juniper in the forest experienced severe water stress and had very low rates of water uptake from July to early September (Fig. 3d) indicating that ecosystem water stores were nearly depleted. However, trees in the clearing also became increasingly water stressed and had sap flow rates nearly as low as trees in the forest by the end of August. This indicated that even the much reduced vegetation cover in the clearing was able to deplete available water stores, although it took four months, instead of only two, to reach similar states of depletion.

Surprisingly, when the drought ended in September 2009, predawn water potentials returned to high values (Fig. 3c), and sap flow velocities remained distinct between sites and species (Fig. 3d). In particular, forest oak trees maintained lower sap flow velocities than oak trees in the clearing. This could indicate loss of hydraulic conductivity, as forest oak trees experienced water potentials as low as -3.3 MPa, which

is low enough to induce xylem embolism in this species and reduce hydraulic conductance until vessels are either refilled or regrown (McElrone et al. 2004). By contrast, oak trees in the clearing did not appear to be similarly constrained. This suggests that woodland trees which regularly encounter summer drought conditions may have reduced transpiration capacity compared to free-standing trees even when water is not limiting. This would tend to reduce differences in the ET of woodlands and savannas/grasslands.

The differences in the sap flow velocities observed between sites in 2009 indicated that differences in stand-level transpiration due to tree density were partially offset by differences in tree-level transpiration. To quantify this effect, stand-level tree transpiration rates for the two sites were estimated. For Ashe juniper, an empirical scaling relationship that linked stem diameter to active sapwood area was used, however, this information was unavailable for live oak. Therefore, an estimation bracket for oak transpiration was used, assuming 50% or 10% active sap flow area as the population average. This placed maximal values for total transpiration rate in 2010, quite realistically, between 5 and 10 mm per day.

Fig. 4 shows that for the 3 month of extreme drought condition in 2009, stand-level transpiration was not different between sites, indicating that the roughly 70% lower stem density in the clearing was compensated by each tree having roughly 70% higher transpiration rates. Estimated forest transpiration was higher in spring and fall, when water was less limiting. Overall, from the end of May 2009 when measurements began to the end of December 2009, juniper stands transpired 30 mm in the clearing and 77 mm in the forest. Oak and juniper together transpired between 43 and 98 mm in the clearing

(depending on the high and low estimate for oak) and between 103 and 206 mm in the forest. Thus, overall transpiration was reduced by half in the clearing, for a total average difference of 0.3 to 0.5 mm per day.

The following year, 2010, was much wetter. Judging from the predawn water potentials, water availability never became limiting to tree transpiration until about August, and then only in juniper, not oak (Fig. 3d). Paradoxically, juniper trees in the clearing had slightly lower water potentials than trees in the forest. Rather than assuming that juniper trees in the clearing experienced more competition for water, a more likely explanation is that the previous drought conditions triggered forest trees to grow deeper root systems, so that when a vertical water gradient established in the summer of 2010, trees in the forest had slightly greater access to water.

Sap flow velocities were much higher in 2010 than in 2009 (Fig. 3). Since sensors were switched to a new setup in February 2010, the possibility that this change was due to changes in sensor sensitivity, rather than actual differences in sap flow, needs to be considered. First, much higher transpiration rates in 2010 are physiologically reasonable, as 2010 had much more precipitation and trees would have produced new sap wood in spring with presumably maximal species-specific hydraulic conductivity. While spring sap flow velocities were lower in 2009, even before the drought, the new wood grown in the beginning of 2009 would have been laid down under conditions of chronic drought stress and may have lacked wide xylem vessels, and lower sap flow velocities could have been expected. Second, there is no break in the sap flow estimates associated with the sensor exchange, rather it appears that sensors were exchanged during a time of rapid but consistent increase in sap flow velocity. Thirdly, diel patterns in sap flow

velocity were similar before and after the sensor exchange. Thus, it is safe to conclude that the qualitative and quantitative changes in sap flow patterns were in fact due to changes in water availability and the re-establishment of high flux capacities in the stems of trees.

Estimates for stand-level juniper transpiration from January to late September 2010 were 91 and 388 mm for juniper in the clearing and forest respectively. Combined oak and juniper estimates were 129 – 283 mm in the clearing and 567 – 1284 mm in the forest. Thus, instead of the estimated 50% reduction in transpiration due to clear-cutting in a dry year, this site experienced an 80% reduction, equivalent to 154 to 283 mm (0.6 to 1.0 mm per day) in the wet year, which is proportional to the difference in tree canopy cover (90 vs. 15%).

These effects of clear-cutting on tree respiration are likely larger than the equivalent effects on ET, but they may have been closer in 2009 than in 2010. Due to the dry conditions in 2009, interception loss, surface evaporation and transpiration by herbaceous plants may have been low for a large portion of the year, and ET would have been largely carried by tree transpiration in both sites. In the summer of 2010, the clearing filled in with herbaceous cover, increasing the contribution of herbaceous transpiration greatly, while it would have been much smaller for the forest, which had little herbaceous understory. This would have likely overwhelmed differences in interception loss, which was expected to be higher in the forest.

#### *Changes in soil water status*

A completely unexpected observation was the persistent difference in soil moisture between the two sites. It would be expected that the two soils, being thin, would have gone through similar changes in soil moisture and converge on the same low values after prolonged periods without rainfall input. Instead, water content in the clearing remained above the water content of the forest even at the height of the 2009 drought.

The possibility of hydraulic lift, perhaps facilitated by the dead roots of felled trees, accounting for this difference, was ruled out due to the lack of observed night-time wetting of the soil in the clearing. It is more likely that a difference in the rock content between the two sites could have been responsible for the site effect, with a higher rock content on the steeper forest slope giving systematically lower volumetric water content readings.

Differences in soil moisture between the two sites appeared to decrease during the summer of 2010 (Fig. 3b). While soil water content in the clearing reached similarly low values in 2009 and 2010, the water content of forest soils remained higher in 2010. A similar effect was also observed by Bates (2000) working on sites in Oregon where western juniper had been removed. This indicates that the forest vegetation did not have the same capacity to draw down soil water content in a wet year, probably due to reduced surface evaporation and lower herbaceous cover.

#### *Analysis of stable isotopes in stem water*

Information about the seasonal and site-specific shifts in stem water stable isotope composition allows inferences about the water sources trees may have used (Ehleringer and Dawson 1992), particularly the contribution of persistent perched water tables.

Perched water tables would have had a similar isotopic composition of water dripping into caves, with isotope ratios for oxygen and hydrogen falling on the global meteoric water line (GMWL). Therefore, if trees took up water from such a source, stem water isotope ratios would have also been close to the GMWL or indicative of a mixture of drip water and evaporatively enriched surface water. However, stem water samples were consistently evaporatively enriched even during the drought period of 2009 (Fig. 8). This indicated that water sources were relatively shallow and subject to direct evaporation, explaining why transpiration rates dropped off so steeply between May and August in the absence of further rainfall inputs.

The seasonal patterns in stem water isotope ratios between the forest and the clearing were superficially similar, but there were site-specific species differences. Sap water isotope ratios of forest oak in July and August were below those of juniper, signifying that oaks began to use a deeper water source than juniper. By early September, water isotope ratios had equalized again: at that time, oak had probably run out of this presumably limited additional water source. Water source separation was also observed in the clearing, although later in summer, presumably due to the slower depletion of the more shallow water source used by both species.

After the drought-breaking rainfall in September, oak trees in the forest were slower to change stem water isotope ratios compared to juniper. This was likely due to impaired water transport capacity, which limited uptake rates for water even when water became freely available again. By contrast, oak trees in the clearing did not lag far behind juniper exchanging “old” stem water with “new” rain water. This provides further

evidence that forest transpiration rates remain limited by hydraulic conductivities after drought events, even after drought conditions are lifted (Fig. 3d).

### *Succession*

In the first year after clear-cutting, a 16% increase in herbaceous cover was observed in the clearing. This was expected, as non-woody plants have faster establishment and growth rates as compared to woody species, and can respond much faster to increased availability of light, soil moisture and presumably soil nutrients. Informal observation in September 2010 indicated that late season grasses and forbs further increased herbaceous cover to the point that little bare ground remained visible. As discussed above, this increase in herbaceous cover would significantly add to ET, particularly in wet years and tend to reduce ET differences between the forest and the clearing. Although not seen in the first two years after clear-cutting in this study, an increase in the density of soil water consumers would eventually remove any differences in soil moisture availability between the forest and the clearing and may help delay the establishment of woody plant species from seed (Van Auken 2004).

However, mechanical clearing usually leaves seedlings and saplings behind, and these may already have roots in the epikarst, below the reach of herbaceous plant roots. Further, saplings have a greater proportion of active sapwood area, thus their contribution to transpiration is proportionally greater than the reduction in total stem area would suggest. Thus, the increased growth potential of saplings added to the increased epikarst water availability and higher light availability will accelerate sapling growth.

Contrary to this expectation, woody plant recruits in this study did not show a significant difference in growth between sites except for branch growth of agarita. However, across species, average height and branch length measurements were consistently greater for saplings in the clearing compared to the forest (Table 6), suggesting that a larger sample size may have revealed significant differences. In a western juniper removal study, a delay of one or more years in woody plant response to clearing was documented (Bates 2000, Everett and Ward 1984, Tausch and Tueller 1977). Thus, there is a possibility that the saplings in this study did not express their full growth potential as they adjusted to the radical change in environmental conditions due to overstory removal.

Moore and Owens (2006) found that juniper seedlings released for 2 years from overstory competition had higher rates of photosynthesis and transpiration than seedlings under adult juniper canopies, supporting the view that the altered environment in the clearing eventually greatly facilitates growth and re-establishment of juniper and other woody species.

Thus, there is a clear expectation that, unless seedling and sapling growth in cleared areas is tightly controlled, the forest will eventually grow back and very likely at a rate that far exceeds the rate of invasion into intact grasslands. Rassmussen and Wright (1989) reported variable recovery rates for woody plant species after juniper removal from a site on the Edwards Plateau, depending on topographic position. Woody plant densities on upper slopes recovered to untreated levels in 13-18 years, whereas plant densities in lower areas remained between 17 and 73% of untreated levels after 18 years. While this could suggest potential water savings over at least 13 years, rates of water

consumption may recover to pre-treatment levels far sooner, since, as seen in this study, rates of water uptake by individual trees increase with decreases in tree density, at least in below-average rainfall years.

*Year-type effect on water savings through clear-cutting: a graphical model*

The study demonstrated contrasting ecohydrological effects of clear-cutting in the first two years after treatment. In 2009 tree transpiration, according to estimates, was limited by epikarst-stored water, for which no difference in stand-level tree transpiration between sites was documented for a period of several months. From June to December, the period for which data were available, cumulative differences in tree transpiration were estimated between 60 and 108 mm. By contrast, in 2010, when water-limitations were minimal, the estimated difference in transpiration from January to September was between 154 to 283 mm. These estimates are a considerable portion of precipitation at the site, but they do not directly translate into differences in ET, which, especially in the wet year, would have been much lower. In addition, differences in ET do not necessarily translate into water savings, as the water not used as ET in the clearing could have been stored in the root zone and used later at a time of water deficit. The data do, however provide a sense for the sensitivity of the clear-cutting treatment to variation in year type characteristics, particularly precipitation inputs.

The graphical model in Figure 9 illustrates the effect of year type on the potential effects of juniper removal on ET in the Edwards Plateau. In Figure 9A, the diagonal line describes the theoretical maximal value for ET, where  $ET = P$ . The two horizontal lines describe realistic limits for forest and grassland ET as limited by energy rather than water

balance. The arrow indicates the precipitation level at which ET is no longer limited by P but instead by PET. The hatched region quantifies potential water savings as a function of annual precipitation, showing that maximal savings can be expected only at high precipitation levels, while dry years might not produce any savings at all.

In an area with karst geology, this relationship may be altered so that ET savings require comparatively higher precipitation inputs. The reason is the inaccessibility of a portion of precipitation due to fast bypass flow through the epikarst. Cave drip rate measurements taken at the study site indicated that there is such a fast flow component. After large rainfall events, flow from cave drips increased dramatically within a few hours or days after precipitation and then slowly receded. This indicates that a portion of precipitation moves quickly through the epikarst, making it essentially unavailable for plant use. In Figure 9B, this is accounted for by subtracting a constant portion of precipitation to give a new estimate for the theoretical limit to ET ( $ET = P - S_{fast}$ ; Fig. 9B). In terms of the water budget equation, the soil drainage term (S) is divided into two components:  $S_{fast}$  and  $S_{slow}$ , only one of which interacts with ET, thus:

$$P - S_{fast} = ET + R + S_{slow} \quad \text{eq 7}$$

The result is that it takes even more precipitation to start seeing ET savings due to vegetation change from forest to grassland (or a denuded state after clear-cutting). Further, since wetter years are often characterized by more intense rainfall events, the relationship between P and maximal theoretical ET could be non-linear and never even intercepting the forest PET.

The model illustrates that long term effects of juniper removal on ET, assuming that grasslands can be maintained as such, is equivalent to the average across year types,

some of which may not accrue any ET savings at all, and others might allow limited savings. Further, potential savings are limited by the proportion of fast bypass flow through the epikarst, which could be very variable across sites and is difficult if not impossible to quantify. This might help explain the discrepancy in the estimates of water savings achieved through clear-cutting and actual field estimates.

### *Conclusion*

This study followed the immediate hydrological consequences of brush removal on the water relations of remaining trees a) to determine the magnitude of change in water availability in the soil/epikarst system and b) to determine which species profited the most from increased water availability, to anticipate successional responses. Water availability in the soil and epikarst differed in a dry year (2009), but approached very similar values at the end of a long summer drought. Water availability was, for the most part, not different during a very wet year (2010). The estimated water savings due to ET reductions in the clearing may have been lower in 2009 than in 2010, driven by differences in precipitation inputs, rather than successional dynamics.

Herbaceous vegetation benefited the most from clear-cutting. Due to fast growth and establishment rates, herbaceous vegetation cover increased by 16% in the first year and likely decreased shallow soil moisture availability. Trees and saplings left standing in the clearing also benefitted from increased water which helped it maintain higher water potentials and, in the case of live oak, limited the loss of hydraulic conductivity.

Table 1. Stem density (stems ha<sup>-1</sup>) of woody plants.

Species	<u>&gt; 65 mm in diameter</u>			<u>25 -65 mm in diameter</u>			<u>&lt; 25 mm in diameter</u>		
	Forest	Clearing	Before clearing	Forest	Clearing	Before clearing	Forest	Clearing	Before clearing
<i>Juniperus ashei</i>	1125.00	186.39	1978.57	500.00	172.07	1333.57	1944.45	2545.25	3118.83
<i>Quercus fusiformis</i>	555.56	322.59	372.77	13.89	623.77	638.10	95819.52	74701.27	74744.29
<i>Diospyros texana</i>	430.56	164.88	172.05	1069.45	989.42	996.59	1625.00	3341.09	3369.77
<i>Celtis reticulata</i>	97.22	35.84	35.84	0.00	0.00	0.00	888.89	444.52	444.52
<i>Quercus buckleyi</i>	27.78	14.34	14.34	0.00	0.00	0.00	8027.78	824.52	824.52
<i>Acacia roemeriana</i>	0.00	35.84	35.84	13.89	28.68	28.68	27.78	1053.95	1061.12
<i>Berberis trifoliolata</i>	0.00	0.00	0.00	0.00	21.51	28.68	2250.00	4122.59	4129.76
<i>Cercis canadensis</i>	0.00	0.00	0.00	13.89	14.34	14.34	347.22	93.21	93.21
<i>Rhus virens</i>	0.00	0.00	0.00	0.00	64.53	71.70	527.78	1505.64	1505.64
Other	0.00	0.00	0.00	0.00	7.17	7.17	111.11	451.69	451.69
Total	2236.11	759.88	2609.41	1611.11	1921.48	3118.83	111569.53	89083.72	89743.34

Table 2. Repeated measures ANOVA of volumetric soil moisture predawn water potentials and sapflow rates.

	Effect	<u>Volumetric soil moisture</u>			<u>Predawn water potentials</u>			<u>Sap flow</u>			
		df	F	p	df	F	p	df	F	p	
May 24 -Sept. 10, 2009	<u>Within-subjects</u>										
	Date	1	108.129	< <b>0.001</b>	1	470.900	< <b>0.001</b>	1	15.546	<b>0.002</b>	
	Date*site	1	2.897	0.140	1	31.648	< <b>0.001</b>	1	1.613	0.228	
	Date*species	--	--	--	1	128.888	< <b>0.001</b>	1	1.111	0.313	
	Date*site *species	--	--	--	1	1.310	0.266	1	1.156	0.303	
	<u>Between-subjects:</u>										
	Site	1	50.376	< <b>0.001</b>	1	79.339	< <b>0.001</b>	1	35.64	< <b>0.001</b>	
	Species	--	--	--	1	142.368	< <b>0.001</b>	1	3	0.109	
	Site * Species	--	--	--	1	0.243	0.627	1	0.475	0.504	
	Sept 11, 2009 – Feb 19, 2010	<u>Within-subjects</u>									
Date		1	85.324	< <b>0.001</b>	1	28.515	< <b>0.001</b>	1	24.227	< <b>0.001</b>	
Date*site		1	1.792	0.229	1	0.943	0.343	1	1.577	0.226	
Date*species		--	--	--	1	2.678	0.117	1	3.016	0.101	
Date*site *species		--	--	--	1	0.295	0.593	1	0.998	0.332	
<u>Between-subjects:</u>											
Site		1	56.969	< <b>0.001</b>	1	1.693	0.208	1	17.077	<b>0.001</b>	
Species		--	--	--	1	11.981	<b>0.002</b>	1	5.116	<b>0.037</b>	
Site * species		--	--	--	1	0.656	0.427	1	0.353	0.56	
Feb 20 - Sept 30, 2010		<u>Within-subjects</u>									
	Date	1	91.691	<b>0.001</b>	1	330.226	< <b>0.001</b>	1	7.612	<b>0.02</b>	
	Date*site	1	4.387	0.104	1	4.947	<b>0.038</b>	1	1.199	0.299	
	Date*species	--	--	--	1	117.053	< <b>0.001</b>	1	0.636	0.444	
	Date*site *species	--	--	--	1	3.706	0.069	1	0.469	0.509	
	<u>Between-subjects:</u>										
	Site	1	32.370	0.005	1	18.977	< <b>0.001</b>	1	0.229	0.643	
	Species	--	--	--	1	121.241	< <b>0.001</b>	1	0.041	0.844	
	Site * species	--	--	--	1	3.165	0.090	1	0.351	0.566	

Table 3. Repeated measures ANOVA of extracted stem water stable isotope analysis.

Site	Effect	df	$\delta\text{D}(\text{‰})$		$\delta^{18}\text{O}(\text{‰})$		
			F	p	df	F	p
Clearing	<u>Within-subjects</u>						
	Date	1	50.271	< <b>0.001</b>	1	37.552	<b>0.001</b>
	Date*species	1	8.961	<b>0.02</b>	1	5.493	0.058
	<u>Between-subjects:</u>						
	Species	1	.281	.613	1	0.928	0.373
Forest	<u>Within-subjects</u>						
	Date	1	83.879	< <b>0.001</b>	1	27.587	<b>0.001</b>
	Date*species	1	7.432	<b>0.034</b>	1	3.499	0.104
	<u>Between-subjects:</u>						
	Species	1	1.616	0.251	1	0.053	0.824

Table 4. Percent vegetative cover measured in 2009 and 2010.

<b>Cover Class/Species</b>	<b>Site</b>	<b>2009</b>	<b>2010</b>	<b>% Change</b>
Grass	Clearing	3.18	11.94	8.76
	Forest	0.42	0.91	0.49
Sedge	Clearing	2.79	7.65	4.86
	Forest	0.36	0.41	0.05
Forb	Clearing	1.78	4.33	2.55
	Forest	0.40	1.21	0.81
<i>Berberis trifoliolata</i>	Clearing	0.85	1.18	0.33
	Forest	2.49	2.25	-0.25
<i>Rhus virens</i>	Clearing	0.56	0.61	0.05
	Forest	0.08	0.00	-0.08
<i>Yucca rupicola</i>	Clearing	0.33	0.15	-0.18
	Forest	0.01	0.00	-0.01
Other	Clearing	0.51	0.70	0.19
	Forest	2.12	1.50	-0.62
<i>Quercus fusiformis</i>	Clearing	14.20	15.00	0.79
	Forest	47.74	52.13	4.39
<i>Celtis reticulata</i>	Clearing	3.72	3.88	0.16
	Forest	4.67	3.44	-1.23
<i>Quercus buckleyi</i>	Clearing	4.52	4.61	0.09
	Forest	5.03	5.14	0.11
<i>Cercis canadensis</i>	Clearing	0.09	0.00	-0.09
	Forest	1.17	0.73	-0.44
<i>Diospyros texana</i>	Clearing	5.54	5.22	-0.32
	Forest	22.15	18.84	-3.31
<i>Juniperus ashei</i>	Clearing	4.56	4.19	-0.37
	Forest	60.14	53.92	-6.23

Table 5. Percent ground cover measured in June 2009 and 2010.

<b>Cover Class</b>	<b>Site</b>	<b>2009</b>	<b>2010</b>	<b>% Change</b>
Litter	Clearing	71.89	58	-13.89
	Forest	84.92	81.29	-3.63
Gravel	Clearing	13.25	17.27	4.02
	Forest	3.33	3.88	0.55
Woody Debris	Clearing	2.25	5.34	3.09
	Forest	1.36	1.1	-0.26
Rock	Clearing	8.41	10.38	1.97
	Forest	12.18	13.59	1.4
Soil	Clearing	2.91	1.61	-1.3
	Forest	0.04	0.06	0.02

Table 6. Univariate ANOVA results of plant height and branch growth measurements. Significant intercepts indicate significant changes in measurements over the study period.

Species	Effect	df	Height		Branch Length		
			F	p	df	F	P
Juniper	Intercept	1	5.853	<b>0.036</b>	1	4.581	0.058
	Site	1	1.819	0.207	1	2.494	0.145
Oak	Intercept	1	5.575	<b>0.04</b>	1	10.357	<b>0.009</b>
	Site	1	0.257	0.623	1	0.144	0.712
Persimmon	Intercept	1	15.141	<b>0.003</b>	1	16.087	<b>0.004</b>
	Site	1	1.375	0.268	1	2.927	0.125
Agarita	Intercept	1	5.535	<b>0.04</b>	1	42.362	<b>&lt; 0.001</b>
	Site	1	3.114	0.108	1	20.388	<b>0.001</b>



Figure 1. Study site photographs. Top photo is of the cleared site, the bottom photo is of the forested site.

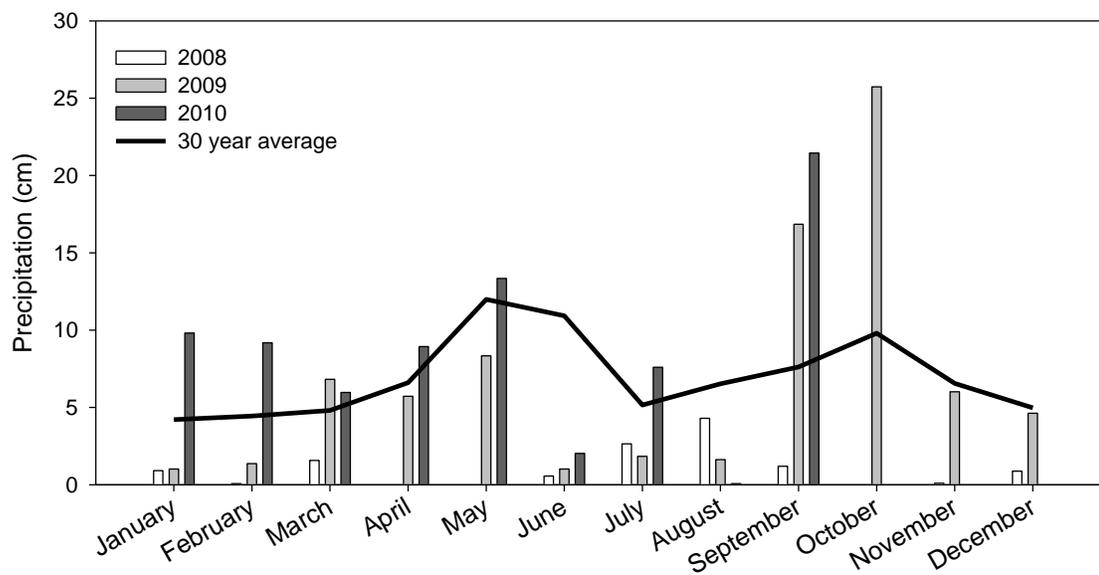


Figure 2. Monthly precipitation trends for 2008-2010 compared to the 30 year average.

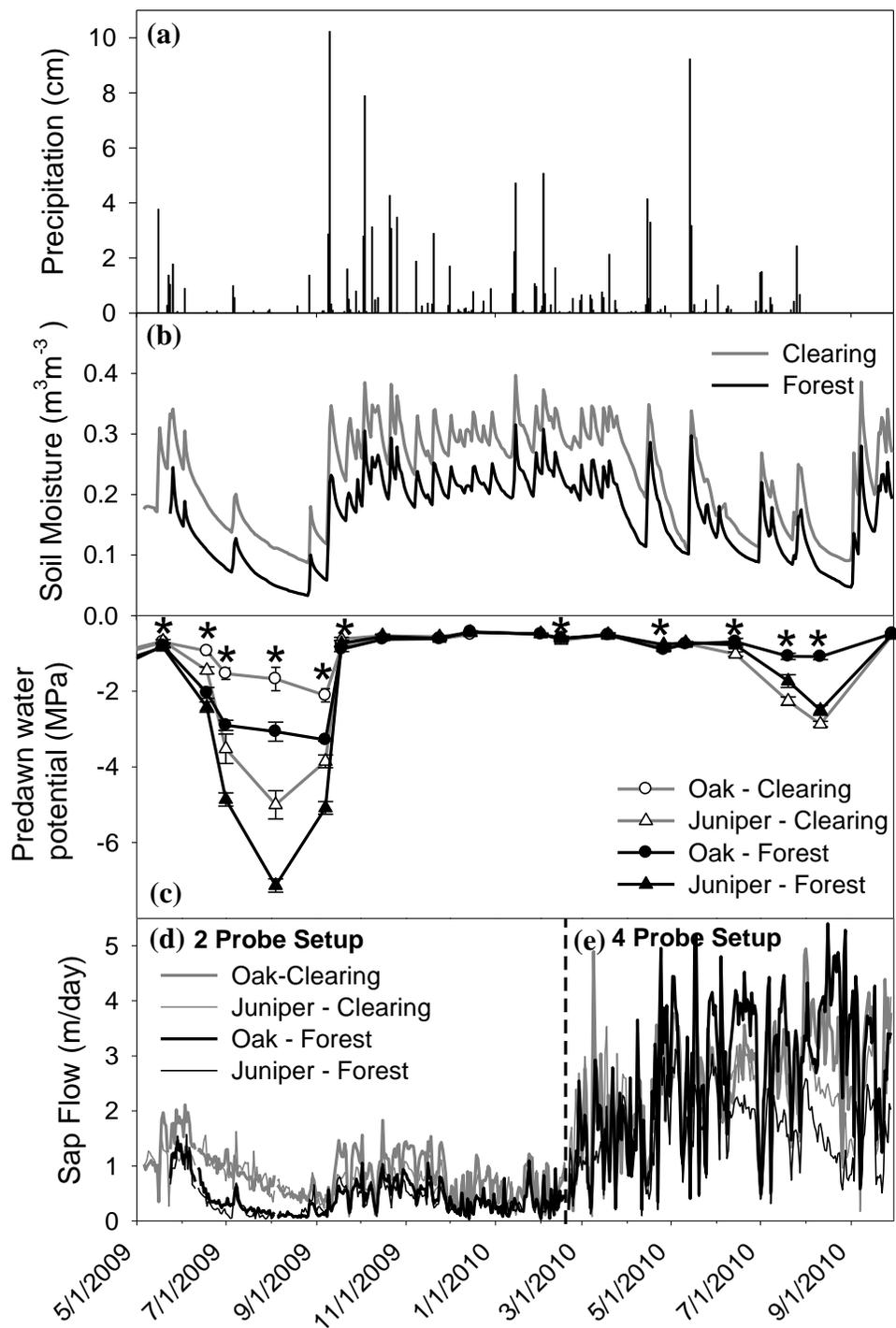


Figure 3. Precipitation (a), volumetric soil moisture (b), predawn water potentials (c) and sapflow rates(d + e) from May 2009 to September 2010. Asterisks (\*) indicate significant differences. Error bars represent  $\pm 1$  SE.

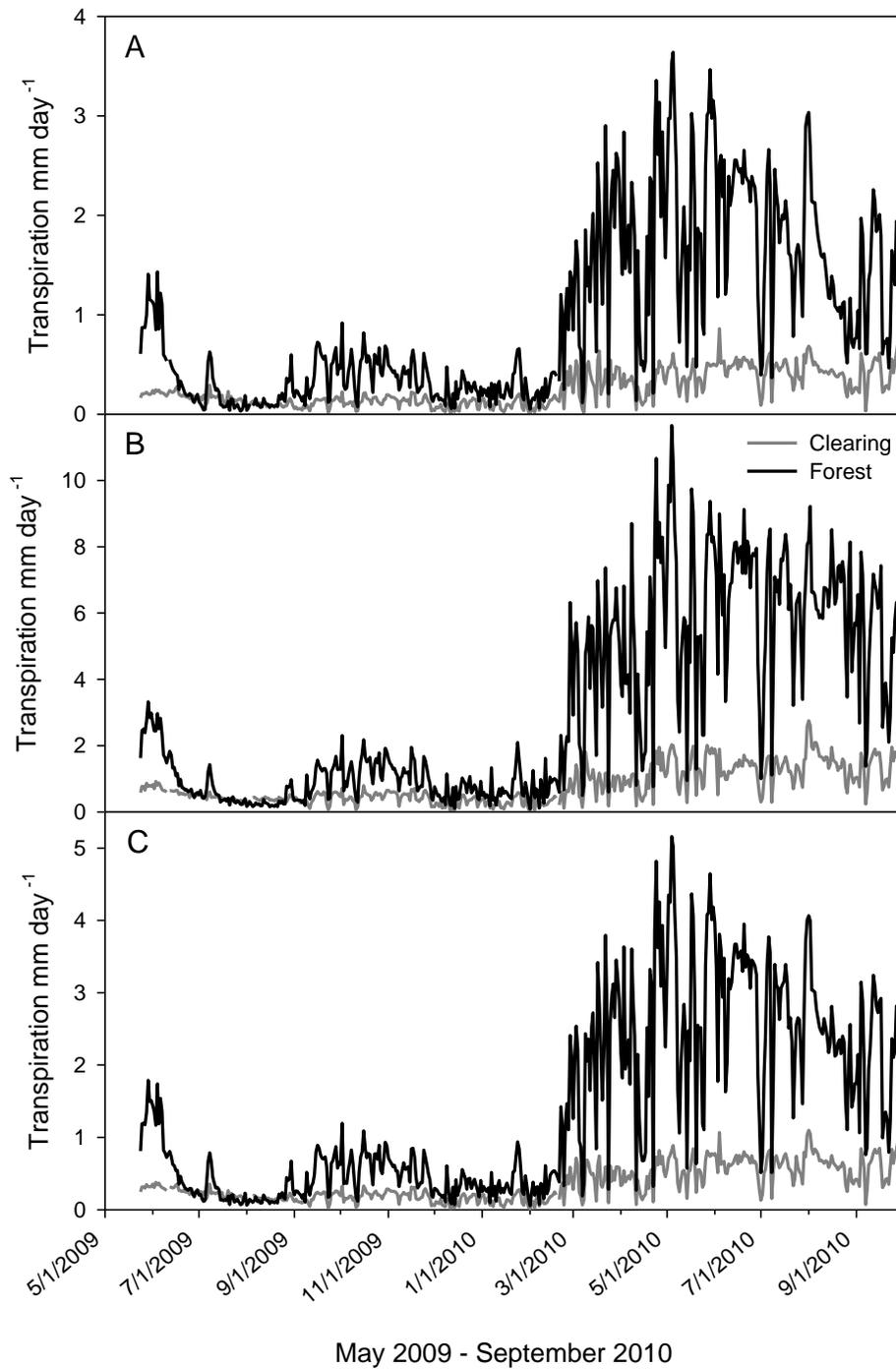


Figure 4. Estimated transpiration levels for each site. A) Estimated stand-level juniper transpiration rate for each site. B) Estimated stand-level transpiration rate for oak and juniper combined using the estimate of 50% of oak stem area as active sapwood area. C) Same as in b) but using the estimate of 10% active sapwood area.

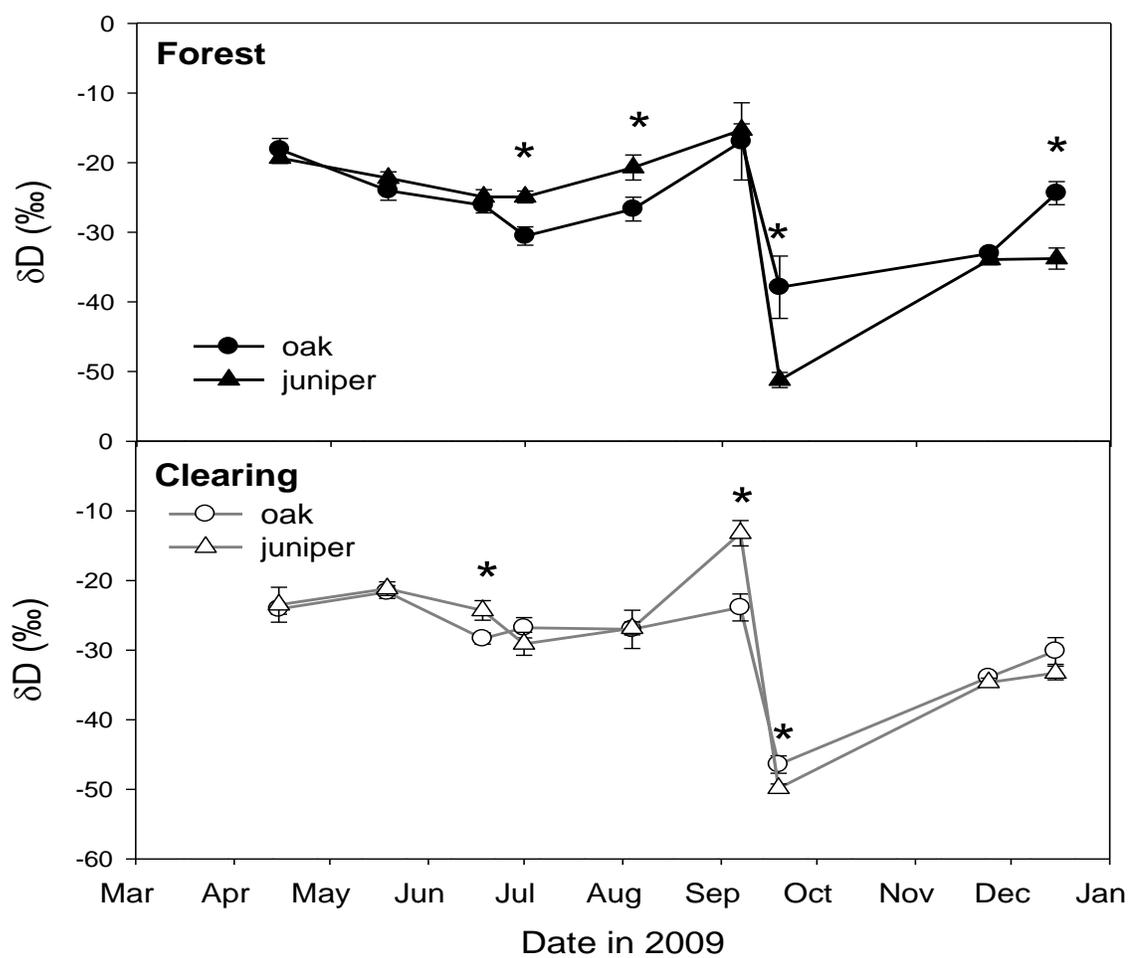


Figure 5. 2009 stem water stable isotope ratios of  $\delta D$  taken from selected trees in the forested and cleared sites. Error bars represent  $\pm 1$  SE. Asterisks (\*) indicate significant differences.

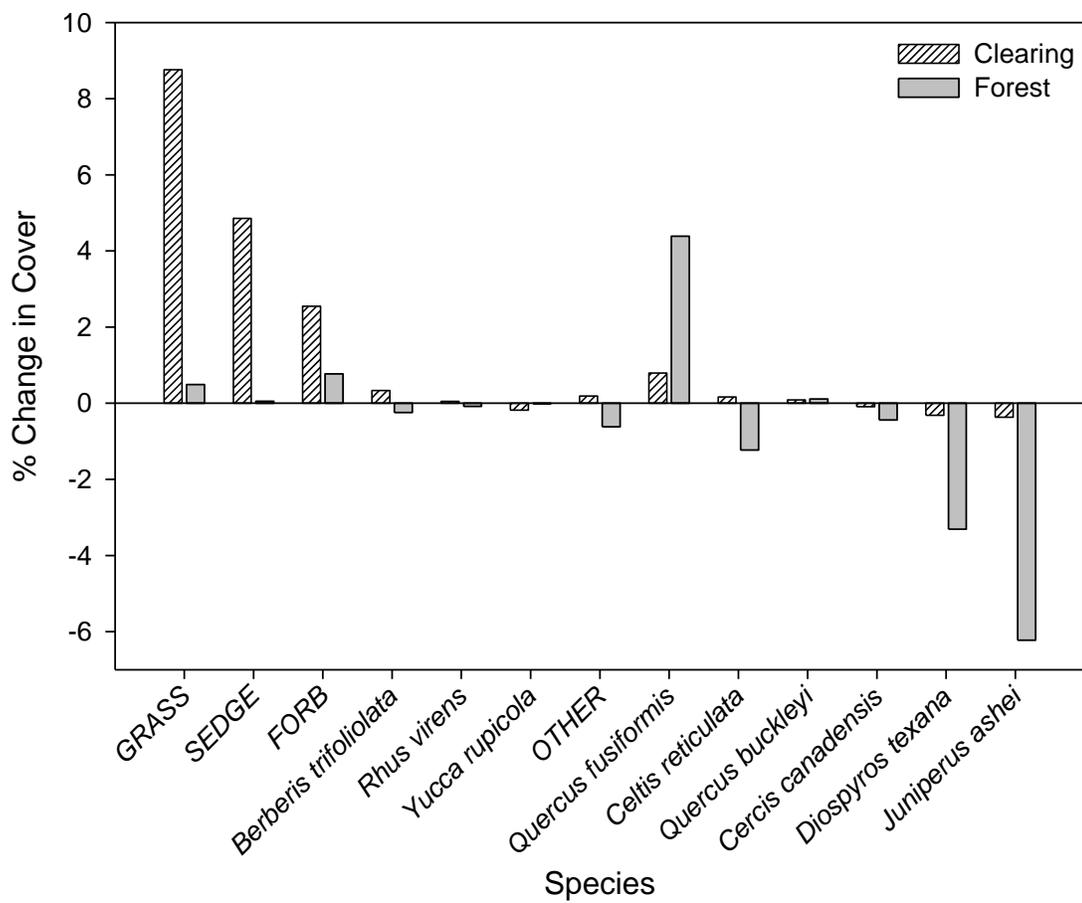


Figure 6. Percent change in measured vegetative cover between 2009 and 2010.

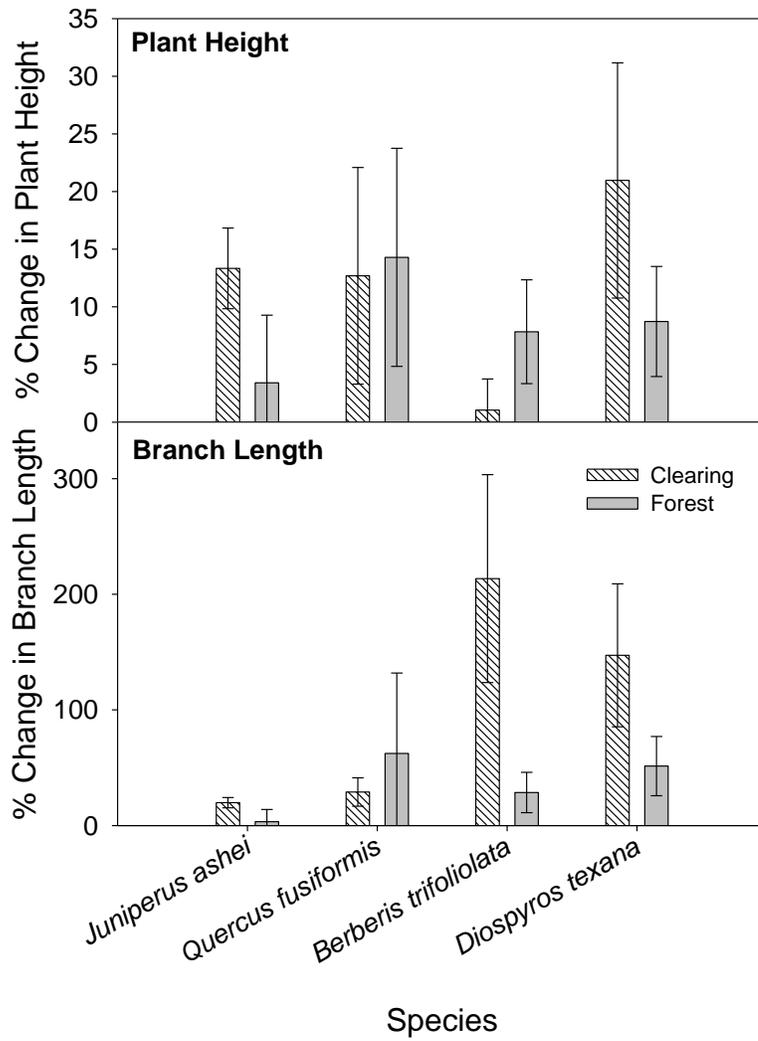


Figure 7. Percent change in growth of plant height and branch length of labeled seedlings and saplings. Error bars represent  $\pm 1$  SE.

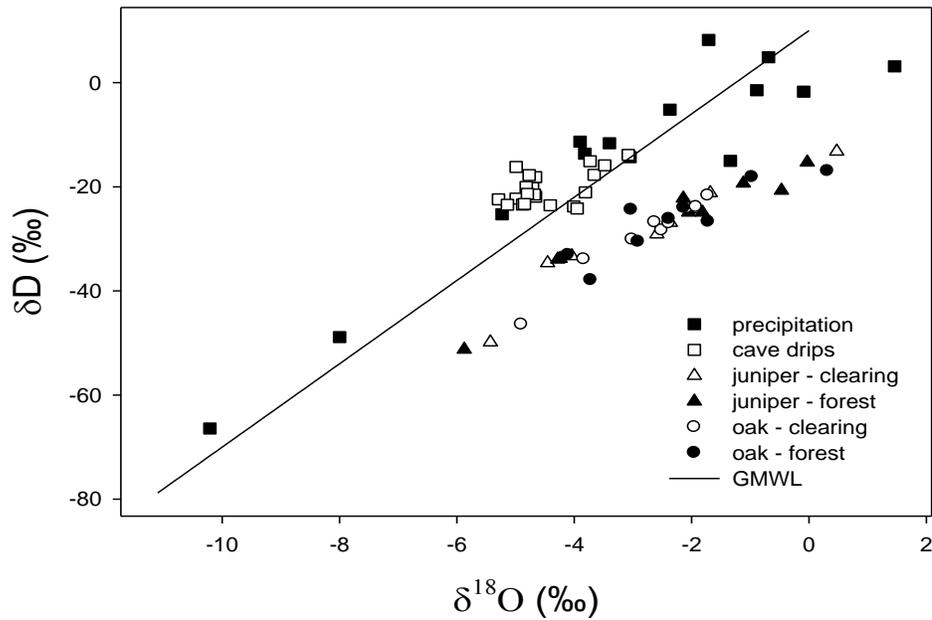


Figure 8. 2009 average stable isotope ratios of  $\delta D$  and  $\delta^{18}O$  in water collected from precipitation, cave drips and trees in the clearing and forested sites for each sampling date.

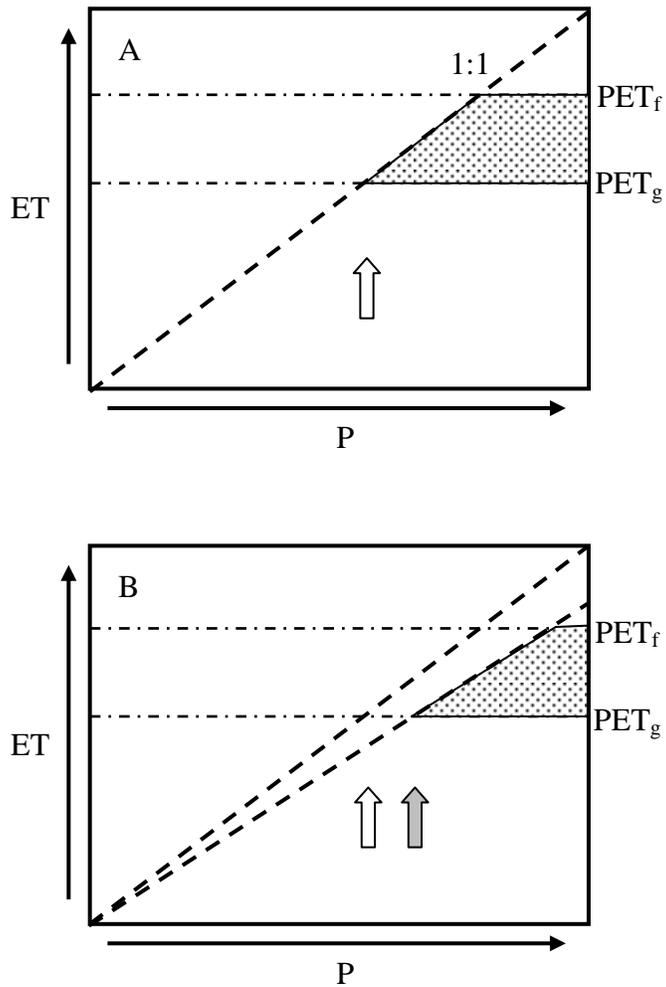


Figure 9. Conceptual model of potential hydrological effects due to juniper removal. A) Effect of vegetation cover on PET. Shaded region represents potential ET savings from juniper removal over a range of precipitation values. Arrow indicates precipitation level where ET savings become possible. B) Effect of bypass flow on potential ET savings from juniper removal. Arrows indicate precipitation level where ET savings are possible with and without bypass flow.

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## VITA

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