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Response of cave air CO_2 and drip water to brush clearing in central Texas: Implications for recharge and soil CO_2 dynamics

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[1] Brush removal is commonly conducted to increase water availability in arid areas, such as central Texas, where water resources are stressed. The effectiveness of brush clearing to enhance recharge, however, remains uncertain as numerous studies have yielded contradictory results. This study assesses the effects of brush clearing on recharge to a cave at Natural Bridge Caverns, central Texas by evaluating changes in drip rate, drip water compositions, cave air CO_2 concentrations, and calcite growth in a cave underlying an area cleared of brush. Drip sites were monitored for 3 years preclearing and 2 years postclearing at five drip sites beneath and seven drip sites not beneath the surface cleared of brush. Physical and chemical drip water parameters exhibit preclearing and postclearing variability. Postclearing drip rate characteristics reflect an initial interval of anomalously heavy rainfall, then a longer dry period. Drip water $^{87}Sr/^{86}Sr$ values do not exhibit preclearing to postclearing variation at sites beneath the cleared area and indicate no change in postclearing water residence time. Significant decreases in postclearing cave air CO_2 are observed at seven of nine drip sites in the cave beneath the clearing. Decreases in cave air CO_2 influence calcite growth, which impacts postclearing drip water Mg/Ca and Sr/Ca. Decreases in cave air CO_2 immediately following brush clearing suggest that a significant portion of soil CO_2 respiration is from tree root respiration rather than from soil microbial activity. Seasonal calcite growth patterns, linked to cave air CO_2, also exhibit variability postclearing and suggest that cave mineral deposits may record historical changes in vegetative cover.

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1. Introduction

1.1. Brush Clearing Impacts on Recharge

[2] Water is an important and limited resource in arid areas, especially in central Texas where brush clearing is a commonly employed strategy to increase recharge to streams and springs. It is proposed that brush clearing reduces rainfall interception and evapotranspiration from woody tree species, such as juniper, that have encroached on historical oak savanna communities. The effectiveness of brush clearing to increase recharge has been intensively studied since the 1990s (Table 1); however, various studies have produced contrary results, leaving the effectiveness of brush clearing to increase recharge in question. In the absence of a consensus of scientific data, anecdotal accounts of increased spring and streamflow following brush removal serve as the major evidence for the effectiveness of brush removal projects [*Wilcox*, 2002].

[3] Brush clearing studies in Texas have investigated the use of water by juniper trees (*Juniperus ashei*), the effect of junipers on recharge, and changes in recharge following brush removal. Evapotranspiration studies have shown that junipers (125.4 mm/yr) have a greater capacity than oaks (72.5 mm/yr) for transpiration [*Owens*, 1996], but evapotranspiration of grasses that grow in following brush removal rival that of the junipers removed [*Dugas et al.*, 1998; *Hester et al.*, 1997]. A molecular investigation identified juniper roots as deep as 8 m, demonstrating that juniper trees can access water beyond the shallow subsurface. Oak tree roots, which are not targeted in brush clearing, however, were found down to depths of 22 m [*Jackson et al.*, 1999]. An isotopic study comparing $\delta^{18}O$ values of juniper xylem, groundwater, and shallow pore water determined that junipers access deeper water in summer seasons and shallow pore water in winter seasons [*McCole and Stern*, 2007]. Evapotranspiration rates measured in a woody covered area, however, were coupled with rainfall and soil moisture content, indicating that woody vegetation relied heavily on water from the shallow soil subsurface, as opposed to the deep subsurface [*Heilman et al.*, 2009].

[4] Studies that have investigated the effect of junipers on infiltration yield contrary results. Several studies conclude

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Table 1. Summary of Previous Brush Clearing Studies

Type	Methods	Results	Substrate	Location	Source
Natural rain events	Brush removed and burned. Plots ranged in size from 0.06 to 0.48 ac (1 ac = 0.00404685642 km^2 or 4046.85642 m^2) and were on slopes ranging from 1% to 61%.	Runoff and soil losses (1–8 t/acre (t/acre = 2.242 t/ha)) were higher on cleared and burned watersheds with slopes greater than 20%.	Edwards Plateau	Callahan County, Texas	*Wright et al.* [1976]
Natural rain events	Streamflow monitored before and after brush removal.	Streamflow increased 40 mm/yr following brush removal.	Edwards Plateau	Ulvade County, Texas	*Wright* [1996]
Natural rain events	Streamflow in nine 3–6 ha watersheds with full, partial, and no removal were compared.	Changes in woody vegetation had little influence on streamflow.	Edwards Plateau	Uvalde County, central Texas	*Wilcox et al.* [2005]
Natural rain events	Streamflow from a 19 ha catchment was monitored before and after removal of 60% of woody vegetation.	Streamflow increased by 46 mm/yr following brush clearing.	Edwards Plateau	Comal County, central Texas	*Huang et al.* [2006]
Natural rain events	Streamflow was monitored before and after brush removal.	Water yields increased 33,500 ac ft (1 ac ft = 1234 m^3) above previous discharge.	Quaternary flood deposits and K limestone	North Concho Watershed, Texas	*UCRA and TIAER* [2007]
Natural rain events	Long-term (decades) streamflow trends were analyzed. A large brush clearing project occurred during this interval.	Decreasing streamflow results from improved rangeland condition due to increased woody vegetation enhancing infiltration. Large-scale brush clearing will not significantly increase stream flow.	Quaternary flood deposits and K limestone	Concho River Basin, Texas	*Wilcox et al.* [2008]
Rainfall simulation	Comparison of 0.5 m^2 grass, oak, and juniper plots before and after brush removal and burning.	There is greater infiltration in oak (200 mm/h) and juniper (180 mm/h) plots relative to grass (76–105 mm/h).	Edwards Plateau	Edwards County, Texas	*Hester et al.* [1997]
Rainfall simulation	Evapotranspiration, rainfall interception, and infiltration characteristics were compared between three plots of grass, oak, and juniper composition.	Interception loss increased (13% to 42%) and deep drainage decreased (16% to 0%) from 100% to 40% grass plots.	Edwards Plateau	Edwards County, Texas	*Thurow and Hester* [1997]
Rainfall simulation	Rainfall simulations conducted over a 90 m^2 plot with 100% juniper canopy cover, and dye tracing used to investigate lateral subsurface flow.	Simulated rainfall infiltrated rapidly and flowed laterally from the base of junipers in the shallow subsurface.	Edwards Plateau	Comal County, Texas	*Taucer* [2006]
Rainfall simulation	Rainfall simulations were conducted before and after brush removal above a 3–4 m deep cave.	Runoff increased following brush removal and recharge to an underlying cave decreased.	Edwards Plateau	Bexar County, Texas	*Bazan et al.* [2008]
Rainfall simulation	Rainfall simulations were conducted over a juniper canopy. Canopy interception, runoff, stemflow, and throughfall, and recharge were measured.	Rainfall interception ranged from 0% to 23%, stemflow from 4% to 9% of throughfall, runoff ~3% of rainfall, and recharge from 8 to 17% of rainfall.	Edwards Plateau	Bexar County, Texas	*Gregory et al.* [2009]
Evapotranspiration	Energy balance and evapotranspiration measurements were made for 2 years in 1700 ha oak-juniper woodland.	Evapotranspiration was responsive rainfall and highly correlated with soil moisture, suggesting woody vegetation relied heavily on rain events and shallow soil moisture.	Edwards Plateau	Hayes County, Texas	*Heilman et al.* [2009]
Evapotranspiration	All junipers taller than 0.5 m was removed in 600 m × 250 m plot, and evapotranspiration was compared to equivalently sized, untreated plot.	A decrease in evapotranspiration of 0.3mm/d was measured for 2 years following brush removal. After 2 years, replacement grasses matched preremoval evapotranspiration rates.	Edwards Plateau	Ulvade County, Texas	*Dugas et al.* [1998]
Evapotranspiration	Gas exchange and leaf area was measured for oak and juniper trees 2.5–3.5 m tall.	Junipers (125.4 L/d) have a greater leaf surface area and consequently transpires more than oak (72.5 L/d).	Edwards Plateau	Ulvade County, Texas	*Owens* [1996]
Modeling	Model of brush removal of areas with heavy, moderate, and low brush cover.	It was estimated that 425% increase in streamflow following 100% removal of brush, and 110% increase if only heavy junipers were removed.	Quaternary flood deposits and Cretaceous limestone	North Concho Watershed, Texas	*UCRA* [1998]
Modeling	Model simulation of 100% brush removal of lands with heavy and moderate brush cover.	Water yields increased (up to 161 mm/yr), and evapotranspiration decreased (up to 146.64 mm/yr).	Variety	8 watersheds, Texas	*Bednarz et al.* [2001]

Table 1. (continued)

Type	Methods	Results	Substrate	Location	Source
Modeling	Woody cover-evapotranspiration regression curves used to assess gains in water yield with decreases in woody cover in six watersheds.	100% increase in water yield in areas with thin soil and where there is the highest water yield potential.	Edwards Plateau	Sutton County, Texas	*Wu et al.* [2001]
Modeling	Model simulations were conducted for various brush management scenarios and results given for 100% removal of brush.	An estimated 46.62 mm/yr reduction of evapotranspiration, increase of 99mm/yr streamflow and increase of 30.6 mm/yr aquifer recharge would occur with 100% brush removal.	Edwards Plateau	Upper Guadalope River, Texas	*Afinowicz et al.* [2005]
Molecular	Identification of tree rooting depth via DNA.	Oak tree roots reached the deepest (18 m), and juniper roots reached between 5 and 10 m.	Edwards Plateau	central Texas	*Jackson et al.* [1999]
Geochemistry	Comparison of soil water, groundwater, and Junipers $\delta^{18}O$ during winter and summer.	Juniper $\delta^{18}O$ were similar to groundwater in the summer and soil water in the winter.	Edwards Plateau	Comal County, Texas	*McCole and Stern* [2007]
Geochemistry	Spring water geochemistry evaluated for pre–brush removal and post–brush removal	Brush removal did not impact spring water geochemistry	Edwards Plateau	Comal County, Texas	*Musgrove et al.* [2010]

that junipers enhance infiltration and that higher rates of runoff occur in the absence of junipers: (1) a comparison of runoff and soil loss on treated and untreated plots of juniper [*Wright et al.*, 1976]; (2) use of rainfall simulations over an area with 100% juniper canopy [*Taucer et al.*, 2008]; (3) a comparison streamflow before and after a basin-wide brush removal [*Wilcox et al.*, 2008]; and (4) measurement of infiltration rates on oak, juniper, and grass plots [*Hester et al.*, 1997]. Yet a separate study comparing oak, juniper, and grass plots demonstrates that greater percentages of rainfall interception (42% versus 13%, respectively) and less infiltration (0% versus 16%, respectively) occur with juniper canopies relative to grass-dominated plots [*Thurow and Hester*, 1997]. An investigation using rainfall simulations over a juniper canopy measured interception rates from 0% to 23% and runoff as 3% of rainfall [*Gregory et al.*, 2009].

[5] Evaluations of recharge pre–brush removal and post–brush removal projects also yield different results. All modeling studies suggest brush removal will yield increases in water yields: a 110% to 425% increase in streamflow with restricted and complete brush removal [*Upper Colorado River Authority* (*UCRA*), 1998], an up to 161 mm/yr increase in water yield [*Bednarz et al.*, 2001], a 100% increase in areas with highest water yield potential [*Wu et al.*, 2001], and a 99 mm/yr increase in streamflow and a 31 mm/yr increase in aquifer recharge [*Afinowicz et al.*, 2005]. Several studies have documented increases in streamflow following brush removal (44 mm/yr [*Wright*, 1996], 46 mm/yr [*Huang et al.*, 2006], and 33,500 ac ft (41×10^9 L) increase in discharge [*UCRA and Texas Institute for Applied Environmental Research at Tarleton State University* (*TIAER*), 2007]), while other studies document unchanging flow conditions [*Bazan et al.*, 2008; *Musgrove et al.*, 2010; *Wilcox et al.*, 2005, 2008]. The studies discussed above are detailed in Table 1.

[6] While the effectiveness of brush clearing to enhance recharge is still in question, key characteristics of a landscape are proposed to increase the effectiveness of brush removal in increasing recharge: climate where rainfall and potential evaporation peak out of phase seasonally, annual rainfall greater than 450–500 mm, thin soils overlying highly karstified or fractured bedrock, and streams with a significant component of base flow. It is proposed that brush clearing is not an effective practice in areas where rainfall occurs in phase with high evapotranspiration rates and where vegetation demands exceed available water (<450–500 mm/yr), as water potentially made available by removing brush would be lost to evaporation and consumption by remaining vegetation. Terrains with thin soils and karstified or highly fractured soils allow for rapid infiltration of water potentially made available by brush removal [*Hibbert*, 1983; *Huxman et al.*, 2005; *Wilcox et al.*, 2006a, 2006b]. Streams that receive a substantial base flow component are proposed to be more likely to have increased streamflow following the removal of brush that transpires subsurface water [*Huang et al.*, 2006].

1.2. Using a Cave Environment to Evaluate Impacts of Brush Clearing on Recharge

[7] This study uniquely approaches the evaluation of brush clearing effects on recharge by using variations in drip rate and drip water compositions to interpret changes in

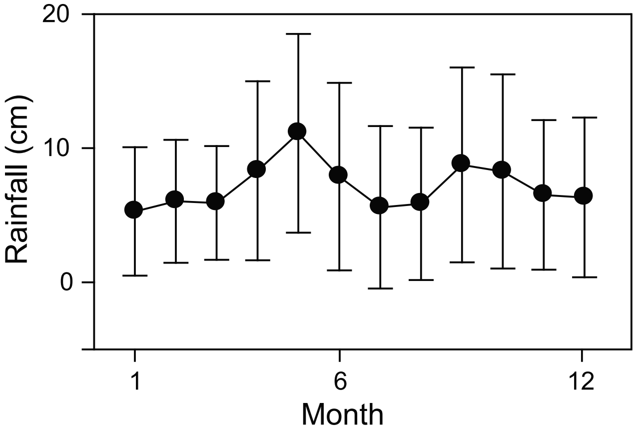

Figure 1. Monthly rainfall average and variability is shown for central Texas. Average monthly rainfall is shown with error bars illustrating one standard deviation, and is based on a rainfall record from 1856 to 2008. Data were retrieved from the National Weather Service Forecast Office for San Antonio, Texas (http://www.srh.noaa.gov/ewx/html/cli/sat/sclidata.htm).

recharge to a cave downslope of and underlying an area cleared of brush. We use drip rate and drip water Mg/Ca, Sr/Ca, and $^{87}Sr/^{86}Sr$ as proxies for recharge. This is the first study that evaluates the effects of juniper removal on recharge to a cave using both physical and chemical characteristics of cave drip water.

[8] We also monitor cave air CO_2 and speleothem calcite growth rate to evaluate brush clearing impacts on soil CO_2 dynamics and speleothem calcite growth patterns. Monitoring cave air CO_2 is critical to understanding how brush clearing alters soil CO_2 dynamics, which is important to understanding land-atmospheric coupling and the feedback loops that will occur with land use and climate change. Documenting postclearing changes in calcite growth is necessary to make accurate interpretations of the causes of variability in drip water compositions. Additionally, monitoring postclearing calcite growth is critical to understanding how temporal variability in vegetative cover is reflected in speleothems, which can be used to reconstruct past climate.

[9] We observe postclearing variability in drip rate, but find changes in drip rate inconsistent and complicated by rainfall variability such that they support neither the hypothesis that brush clearing impacts recharge nor the null hypothesis that brush clearing does not impact recharge. Drip waters show postclearing variability Mg/Ca and Sr/Ca that is related to changes in cave air CO_2, but no variability in drip water $^{87}Sr/^{86}Sr$ values. Invariable $^{87}Sr/^{86}Sr$ values suggest that the brush clearing did not affect recharge. We observe significant postclearing decreases in cave air CO_2 and discuss the various implications of this result on CO_2 dynamics and effects in the subsurface.

1.3. Ecohydrologic Setting

[10] The project area is in central Texas on the Edwards Plateau, which is a karstified Cretaceous marine carbonate platform. Monitoring was conducted in Natural Bridge Caverns, which recharges the Trinity aquifer and is in the contributing zone of the Edwards aquifer [*Elliott and Veni*, 1994]. Natural Bridge Caverns consists of two caves (north and south) formed in the cavernous layer of the upper Glen Rose Limestone and the bottom portion of the Kainer Formation [*Small and Hanson*, 1994]. The cave has a lateral extent of 1160 m and a maximum depth of 75 m [*Elliott and Veni*, 1994].

[11] The average annual precipitation is 750 mm. Long-term annual rainfall peaks in fall and spring seasons, but interannual variability makes timing of rainfall unpredictable (Figure 1). Rainfall occurs during both low- and high-evapotranspiration conditions, and a small number of large, high-intensity rainfall events provide the majority of annual rainfall.

[12] Soils at Natural Bridge consist of the Comfort-Rock Outcrop Complex, which is composed of 42.5% clay, 29.4% silt, and 28.1% sand and has a hydraulic conductivity of 1 μm/s (http://soils.usda.gov/survey/geography/ssurgo/). Soils thicknesses are generally thin (<20 cm). A recent study at Camp Bullis (20 km away) demonstrated that water movement through soils is variable. Preferential pathways, such as desiccation cracks, roots, and wormholes, allow for rapid transit times (up to 2.4 m/h) that contrast with much slower infiltration rates through the soil matrix [*Taucer*, 2006]. Soils overlay fractured and karstified limestone, which is ideal for rapid infiltration. The surface is gently sloping (<10%) and covered with oak (*Quercus*), juniper (*Juniperus*), savanna grasses, and cacti. In the area of focus, junipers make up approximately 95% of the canopy.

[13] The site has the proposed characteristics (i.e., a climate where peak rainfall does not regularly occur during the season of highest potential evaporation; greater than 500 mm annual rainfall; and thin soils and fractured, karstified bedrock that could allow for rapid infiltration of water potentially made available by brush clearing), discussed in section 1.1, that maximize the potential for brush clearing to increase recharge. Note that the characteristics of this system allow water to bypass vegetation quickly, and do not universally apply to other systems.

2. Methods

2.1. Field Data and Sample Collection

[14] Data collection began in 1998 at seven sites within the north (three) and south (four) caves at Natural Bridge Caverns (Figure 2). In 2004, data collection began at five sites in the south cave beneath an area that was going to be cleared of brush. Sites beneath the clearing area are termed clearing area, and sites from the rest of the cave are termed nonclearing area. Drip sites range in depth from 30 to 60 m. Sampling trips were conducted every four to six weeks to measure drip rate (at 11 sites) and cave air CO_2 (at 12 sites) through August 2009, and to collect drip water samples (at nine sites), through April 2008. Drip rate was monitored continuously, instrumentation allowing, at three clearing area sites from April 2007 to May 2009. Cave air CO_2 was measured with a Telaire 7001 CO_2 meter (±5% [*Banner et al.*, 2007]). Calcite growth rate was measured at three nonclearing area sites (one in the north cave and two in the south cave) by placing glass plates beneath drips for four to six weeks and measuring the amount of calcite grown for a particular time interval [*Banner et al.*, 2007]. Standard deviations of calcite plate weights are 0.0003 g for January

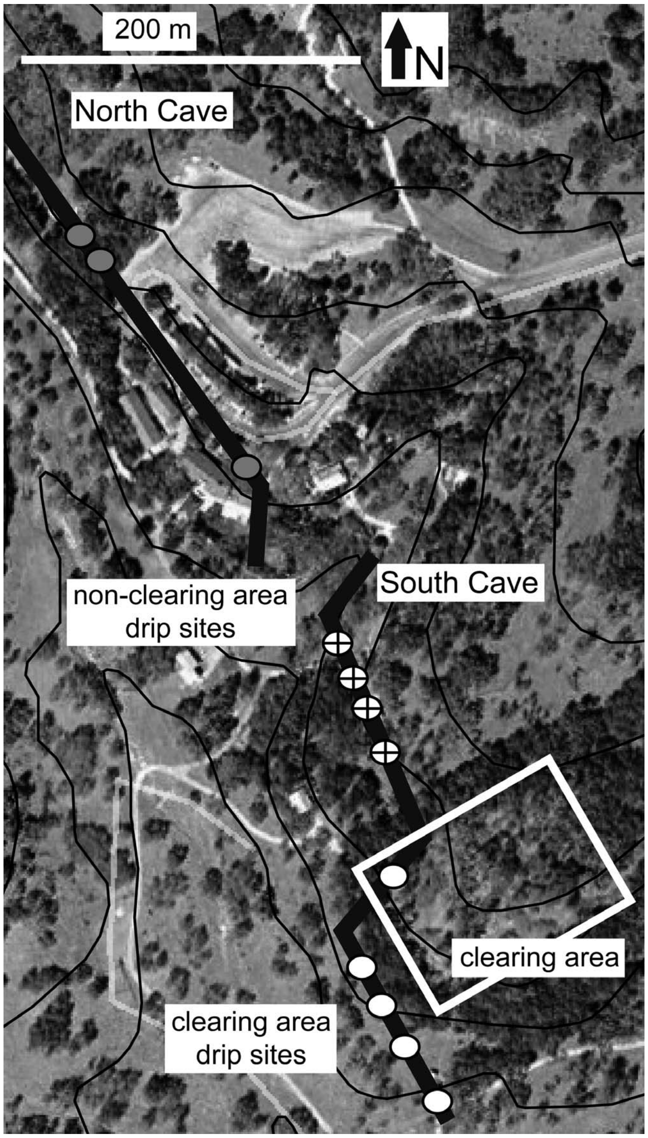

Figure 2. The trend of the north and south caves and location of the clearing area are delineated. Drip site locations in the clearing (white circles) and nonclearing area (circled crosses) are shown. Topographic lines demark 10 foot (3 m) intervals decreasing from NW to SE. Note that the majority of the north cave is downslope of a parking lot. The base image was obtained from Google Earth.

2007 to September 2007, 0.002 g for October 2007 to December 2007, 0.0002 g for January 2008 to August 2009. Calcite plate weights prior to 2007 have a standard deviation of 0.0003 g [*Banner et al.*, 2007]. Rainfall data was collected by an on-site weather station and supplemented by a U.S. Geological Survey (USGS) station (08167347) that is located approximately 10 km to the northwest of the project site.

2.2. Mg/Ca, Sr/Ca, and $^{87}Sr/^{86}Sr$ Values as Proxies for Recharge

[15] Understanding the controls on drip water compositions will be useful in determining how the variations in drip water composition reflect changes in recharge. There are two significant controls on drip water compositions relevant to this study: (1) extent of water-rock interaction, which is dictated by water residence time and (2) amount of calcite precipitation. Increasing extents of water-rock interaction will increase drip water Mg/Ca and Sr/Ca and decrease $^{87}Sr/^{86}Sr$ values. Vadose water in central Texas karst acquires its initial Mg/Ca, Sr/Ca, and Sr isotope signature from the soil through which it infiltrates. As water subsequently infiltrates through and reacts with host carbonate rocks, it attains higher Mg/Ca and Sr/Ca and lower $^{87}Sr/^{86}Sr$ values. Mg/Ca and Sr/Ca values increase as water progressively dissolves carbonate minerals with higher Mg and Sr concentrations than the calcite that is reprecipitated [*Banner and Hanson*, 1990]. Progressive carbonate mineral dissolution results in decreasing $^{87}Sr/^{86}Sr$ values of water, tracking the shift from a soil source to a Cretaceous carbonate rock source of Sr. The length of time that water is in contact with the host carbonate rock (i.e., water residence time) is a principal factor in determining the extent to which water-rock interaction occurs and is dictated by amount of water flux (i.e., amount of rainfall and infiltration) and type of flow route (diffuse versus conduit). At the same drip site, changes in water compositions resulting from variations in extent of water-rock interaction will be a reflection of changing water residence time due to changes in water flux.

[16] Calcite precipitation is also an important control of drip water compositions. Higher drip water Mg/Ca and Sr/Ca occur with increasing amounts of calcite precipitated from the water as Ca is preferentially partitioned into the calcite crystal lattice, and the amount Mg and Sr in the water increase relative to Ca. $^{87}Sr/^{86}Sr$ values, however, are not altered by calcite precipitation and can be used as a direct proxy for water residence time [*Banner et al.*, 1996]. Mg/Ca and Sr/Ca can be used as proxies for water residence time at sites where the influence of calcite precipitation is negligible relative to water residence time. Previous work has demonstrated that Mg/Ca and Sr/Ca at four sites in the clearing area and one site in the nonclearing area are influenced by seasonal calcite precipitation that is dictated by cave air CO_2 concentrations (C. Wong, Seasonal drip-water Mg/Ca and Sr/Ca variations driven by cave ventilation: Implications for speleothem paleoclimate records, submitted to *Geochimica et Cosmochimica Acta*, 2010). The influence of cave air CO_2 concentrations will make interpretation of postclearing Mg/Ca and Sr/Ca more complex.

2.3. Analytical Methods

[17] All geochemical analyses were conducted in the Department of Geological Sciences at the University of Texas at Austin. $^{87}Sr/^{86}Sr$ isotopic compositions were measured following methods of *Banner and Kaufman* [1994] using a seven collector Finnigan-MAT 261 thermal ionization mass spectrometer. The mean National Institute of Standards and Technology (NIST) SRM 987 standard value measured during the duration of the study was 0.710261 (2 sigma = 0.000014, $n = 56$). The procedural lab blank values were negligible (17–25 pg) relative to a typical sample size of 200 ng. Replicate $^{87}Sr/^{86}Sr$ analyses on eight unknowns are within 0.000010. Cation concentrations were measured on an Agilent 7500ce quadruple inductively coupled plasma–mass spectrometer (ICP-MS). Analytical uncertainty based on analysis of known external standards

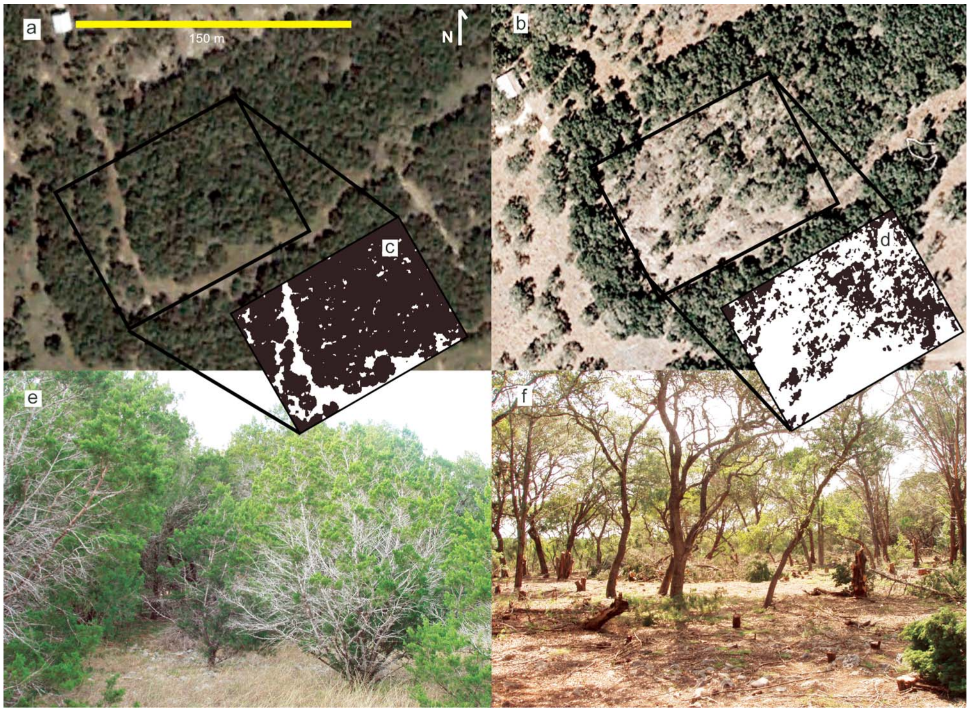

Figure 3. Clearing area (a) pre–brush removal and (b) post–brush removal aerial images, along with (c and d) output images of canopy analysis produced in ImageJ. Aerial images were obtained from Google Earth. (e) Pre–brush removal and (f) post–brush removal photos taken within the clearing area.

for Ca, Mg, and Sr is 10%, 8%, and 6%, respectively, and for Mg/Ca and Sr/Ca is 6% and 9%, respectively. Blank values range from below detection limit to 0.1 ppm for Mg, below detection limit to 0.2 ppm for Ca, and are below detection limit for Sr. All drip water samples are unfiltered. *T* tests are used to evaluate differences in preclearing and postclearing parameters, and significant differences are defined as those with a p value < 0.05.

2.4. Brush Removal

[18] Brush removal was conducted from late April to early July of 2007, following 3 years of monitoring in the cave below. Juniper trees were targeted for removal as their present-day abundance and range encroaches on historic oak savanna habitat. Brush removal consisted of removal of juniper trees smaller than 0.3 m in diameter and juniper trees of any size located adjacent to oak trees. Juniper trees that were larger than 0.3 m in diameter were trimmed down to one to two main trunks, and branches were removed up to about 2 m in height. Removal was conducted with chainsaws, and cut debris was removed manually from the cutting area. Brush clearing took place on several discontinuous days during the period of April 2007 to July 2007, and approximately 8000 m^2 were treated (Figure 3). ImageJ 1.43 software [*Abramoff et al.*, 2004] was used to create binary preclearing and postclearing images and analyze precanopy (83%) and postcanopy (33%) coverage (Table 2). The remaining canopy area (2700 m^2) was converted to remaining leaf area of woody biomass (33,200 m^2) using the linear equation for the correlation ($r^2 = 0.97$) between leaf area and canopy area for junipers calculated by *Hicks and Dugas* [1998]. This method is an overestimation of the amount of leaf area remaining because (1) while the canopy of large junipers were unaltered, branches from these trees were removed up to 2 m in height, and (2) oak trees were not removed, and oaks have less leaf area than a juniper for the same canopy area. While the majority of previous brush clearing studies have removed 100% of brush cover, *Huang et al.* [2006] observed increased streamflow following the removal of 60% of woody vegetation, and the model used by *Afinowicz et al.* [2005] produced reduction of evapotranspiration under brush clearing scenarios that ranged from the removal of 23–96% of heavy brush.

3. Results and Discussion

[19] Postclearing drip rate and drip water Mg/Ca and Sr/Ca variations are not easily interpreted because of the complicating factors of anomalously heavy rainfall coincident with the end of the brush clearing process and the impact of cave air CO_2 concentrations on drip water Mg/Ca and Sr/Ca. Temporally invariant preclearing and postclearing drip water $^{87}Sr/^{86}Sr$ values at clearing area sites suggest that the brush clearing conducted did not change recharge

Table 2. Brush Removal Summary

	Canopy Area[a] (m^2)	Percent	Leaf Area[b] (m^2)
Preclearing	6700	83	83,200
Postclearing	2700	33	33,200

[a] Treatment area was 8000 m^2.

[b] Calculated from the correlation between canopy and leaf area [*Hicks and Dugas*, 1998].

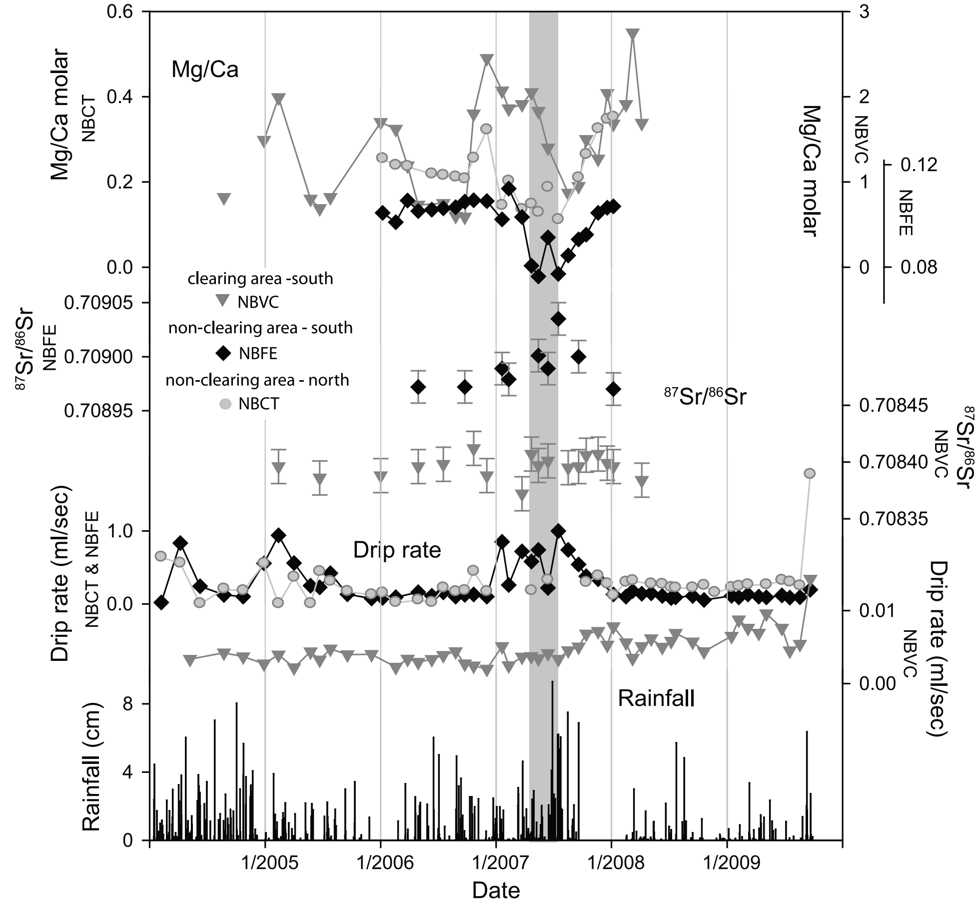

Figure 4. Time series of drip water Mg/Ca, $^{87}Sr/^{86}Sr$, drip rate, and rainfall are shown for representative sites of clearing area and nonclearing area north and south cave sites. The time interval in which clearing occurred is delineated with a gray bar.

dynamics. Reduced cave air CO_2 concentrations postclearing suggest that the brush clearing impacted soil zone CO_2 dynamics. There is strong evidence that reductions in cave air CO_2 were responsible for postclearing changes in cave drip water Mg/Ca and Sr/Ca. Although the drip rate results are too inconsistent to draw any conclusions, the invariant $^{87}Sr/^{86}Sr$ values suggest that the reduction of canopy coverage from 83% to 33% over a 8000 m^2 plot did not impact recharge to drip sites at a 30–60 m depth within a cave beneath and downslope of the clearing area within the time interval and rainfall conditions of this study. The cave air CO_2 results, however, suggest that the brush clearing altered soil CO_2 dynamics, which resulted in significant declines in cave air CO_2.

3.1. Rainfall

[20] During the time period of data collection, there were 2 years of relatively high rainfall, 2004 and 2007 at 1450 mm and 1200 mm, respectively, and 3 years of below average rainfall, 2005, 2006, and 2008 at 510 mm, 720 mm, and 408 mm, respectively (Figure 4). There was 200 mm of rainfall from January to August 2009 when data collection for this study ended. From September to November of 2004 there were 27 rain events yielding a total of 529 mm, causing flooding of the lowest parts of the south cave. There were seven events exceeding 25 mm/d and a maximum rate of 88.9 mm/d. From June to August of 2007 there were 39 rain events yielding a total of 700 mm, causing flooding of the southern half of the south cave and parts of the north cave. There were eight events exceeding 25 mm/d and a maximum rate of 91.4 mm/d.

3.2. Preclearing and Postclearing Drip Rate Characteristics

[21] Drip rates ranged from 0 to 355 mL/min with coefficients of variation ranging from 0.15 to 2.46 (Figure 5). There were varying directions and degrees of change in drip rate following brush removal. Note that (1) clearing area sites exhibit both increases (three) and decreases (two) in average drip rate, (2) nonclearing area sites exhibit increases (two), decreases (three), and no change in drip rate (one), and (3) differences were only significant ($p < 0.05$) at five of the 11 sites (Table 3). Using a classification scheme based on maximum drip rate and drip rate variability adapted from *Baldini et al.* [2006], sites are classified as supplied by dominantly diffuse (low maximum drip rate and drip rate variability) or conduit flow (high maximum drip rate and drip rate variability). Three sites (all clearing area sites) are classified as supplied by dominantly diffuse flow, and the remaining are classified by conduit flow (two clearing area

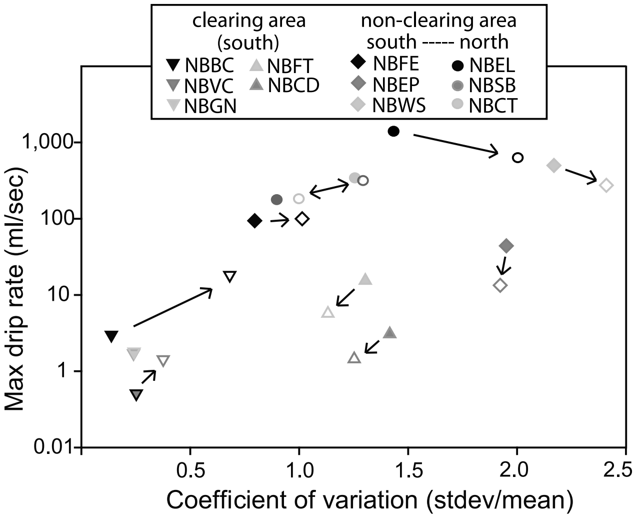

Figure 5. Changes from preclearing (solid symbols) to postclearing (open symbols) maximum drip rate and drip rate variability are shown.

and six nonclearing area sites) prior to brush removal. Following brush removal, classifications do not change, but sites exhibit varying shifts in maximum drip rate and drip rate variability (Figure 5). Note that (1) two of three diffuse clearing area sites exhibit higher maximum drip rates and drip rate variability and (2) four of eight conduit sites (two clearing area and two nonclearing area) exhibit lower maximum drip rates and variability (Figure 5). Drip rate responses to heavy rainfall events at seven of nine sites were greater in 2007, following the brush clearing, relative to 2004, prior to the brush (two sites were inaccessible because of flooding (Table 4)).

3.3. Interpreting Brush Clearing Impacts on Drip Rate

[22] Changes in drip rate between preclearing and postclearing intervals can be indicative of altered recharge dynamics. The type of flow path that supplies drip sites is important to consider as different types of flow paths accommodate different types of recharge. Drip sites fall on a continuum between conduit-dominated and diffuse-dominated end-members [*Baldini et al.*, 2006]. Conduits offer a larger and more direct route from the surface, and thereby allow higher volumes of flow that respond quickly to rain events. Diffuse routes through the pore space of the host carbonate rock are more tortuous and result in a slow, steady drip water supply. Holding rainfall conditions constant, a decrease in drip rate magnitude and drip rate variability of a conduit-supplied site may result from less rapid infiltration following a rain event, perhaps

Table 3. Mean and *p* Values for Drip Rate, Drip Water Compositions, and CO_2 Concentrations Preclearing and Postclearing

Site	Mg/Ca (mol/mol)			Sr/Ca (mmol/mol)			Ca (ppm)		
	Preclearing	Postclearing	*p*[a]	Preclearing	Postclearing	*p*[a]	Preclearing	Postclearing	*p*[a]
Clearing area									
NBVC	1.36	1.7	>0.05	1.35	1.57	>0.05	42.8	31.2	>0.05
NBBC	0.82	0.91	<0.05	0.69	0.7	>0.05	56.6	53.4	>0.05
NBGN	0.97	1.55	<0.01	0.88	1.27	<0.01	53.3	30.8	<0.01
NBCD	0.3	0.42	>0.05	0.49	0.64	>0.05	73.0	45.2	<0.01
NBFT	0.03	0.02	<0.05	0.2	0.17	<0.05	124.6	137.9	>0.05
Nonclearing area									
North									
NBCA	0.21	0.23	>0.05	0.39	0.44	>0.05	62.5	71.4	>0.05
NBEL	0.17	0.11	<0.01	0.33	0.29	<0.01	61.0	80.5	<0.01
South									
NBWS	0.05	0.05	>0.05	0.2	0.19	>0.05	113.3	126.1	<0.01
NBFE	0.11	0.09	<0.01	0.23	0.2	<0.01	107.1	127.9	<0.01

Site	$^{87}Sr/^{86}Sr$			Drip Rate (mL/min)			Cave Air CO_2 (ppm)		
	Preclearing	Postclearing	*n*	Preclearing	Postclearing	*p*[a]	Preclearing	Postclearing	*p*[a]
Clearing area									
NBVC	0.70837–0.70841	0.70840–0.70841	18	0.2	0.37	<0.01	10,700	3,400	<0.01
NBBC	0.70833–0.70835	0.70833–0.70835	10	2.72	3.34	>0.05	11,600	3,300	<0.01
NBGN	0.70839–0.70874[b]	0.70838–0.70840	10	0.69	0.71	>0.05	12,800	3,200	<0.01
NBCD	0.70884–0.70895	0.70892–0.70896	11	0.33	0.12	>0.05	10,700	6,500	>0.05
NBFT	0.70878–0.70883	0.70880–0.70881	9	20.99	2.57	<0.01	11,500	4,000	<0.01
Nonclearing area									
North									
NBCT	NA[c]	NA		13.87	16.53	<0.01	3,000	2,500	>0.1
NBEL	NA	NA		177.5	41.76	<0.01	3,600	2,600	>0.1
NBSB	NA	NA		29.95	25.8	<0.05	2,700	2,500	>0.1
South									
NBWS	NA	NA		18.37	18.39	>0.05	20,200	3,000	<0.01
NBFE	0.70897–0.70899	0.70897–0.70904	9	1.49	1.78	>0.05	12,100	5,500	<0.05
NBEP	NA	NA		2.64	1.01	>0.05	10,100	3,500	<0.01
NBOP	NA	NA		NA	NA		7,900	1,800	>0.01

[a] The *p* values <0.05 indicate that differences between before and after clearing time intervals are significant.
[b] Anomalously high relative to all the other measurements at NBGN.
[c] NA, not applicable because of no or limited measurements.

Table 4. Drip Rate Response to Intense Rainfall Intervals of 2004 and 2007

	Flow Route	Average (mL/min)	2004 (mL/min)	2007 (mL/min)
Clearing area				
NBVC	diffuse	0.29	0.25	0.74[a]
NBBC	diffuse	2.99	2.94	10.9
NBGN	diffuse	0.70	0.88	1.1
NBCD	conduit	0.23	0.23	flooded
NBFT	conduit	1.29	92	103[b]
Nonclearing area				
North				
NBEL	conduit	117	120	355
NBCT	conduit	0.54	34	flooded
NBSB	conduit	0.57	37	65
South				
NBWS	conduit	23	23	165
NBFE	conduit	19	3.7	6
NBEP	conduit	2.07	0.46	8.04

[a] Peak rate occurred 5 months after rainfall.
[b] Measured continuously with tipping bucket.

because of increased runoff. Alternatively, an increase in average or maximum drip rate and drip rate variability of a diffuse site may result from a greater quantity of water in pore space above the cave, perhaps because of less evapotranspiration.

[23] Drip rate characteristics exhibit various types of variability following brush removal. In the clearing area, a conduit-supplied site (NBFT) exhibits a significant decrease (87%) in average drip rate and a diffuse-supplied site (NBVC) exhibits a significant increase (85%) in drip rate (Table 3). The other conduit-supplied site (NBCD) and two diffuse-supplied sites (NBBC and NBGN) in the clearing area also exhibit decrease and increases in average drip rate, respectively, although the differences are not significant. These changes in average drip rate are consistent with the shift of diffuse-supplied sites to higher maximum drip rates and drip rate variability and conduit-supplied sites to lower maximum drip rates and drip rate variability following brush removal (Figure 5).

[24] These results suggest that brush removal both increased runoff and reduced evapotranspiration, but become inconclusive when evaluated in the context of rainfall variability. The conclusion of the brush removal in the summer 2007 was coincident with anomalously high rainfall, and followed by extremely dry conditions that persisted into the winter of 2009 (Figure 4). All drip sites responded to the heavy rainfall of 2007, including dominantly diffuse-supplied sites that did not respond to heavy rainfall in 2004 (Table 4). Higher drip rate responses in 2007 relative to 2004 may be due to brush removal or variations in rainfall conditions. Rainfall in 2007, 700 mm, was 25% more than the rainfall in 2004, 529 mm. The additional rainfall could have filled and surpassed a storage capacity threshold not reached in 2004, causing higher maximum and average drip rates at diffuse-supplied drip sites. Additionally, drip rate characteristics at diffuse-supplied sites would be less affected by persistent dry conditions relative to

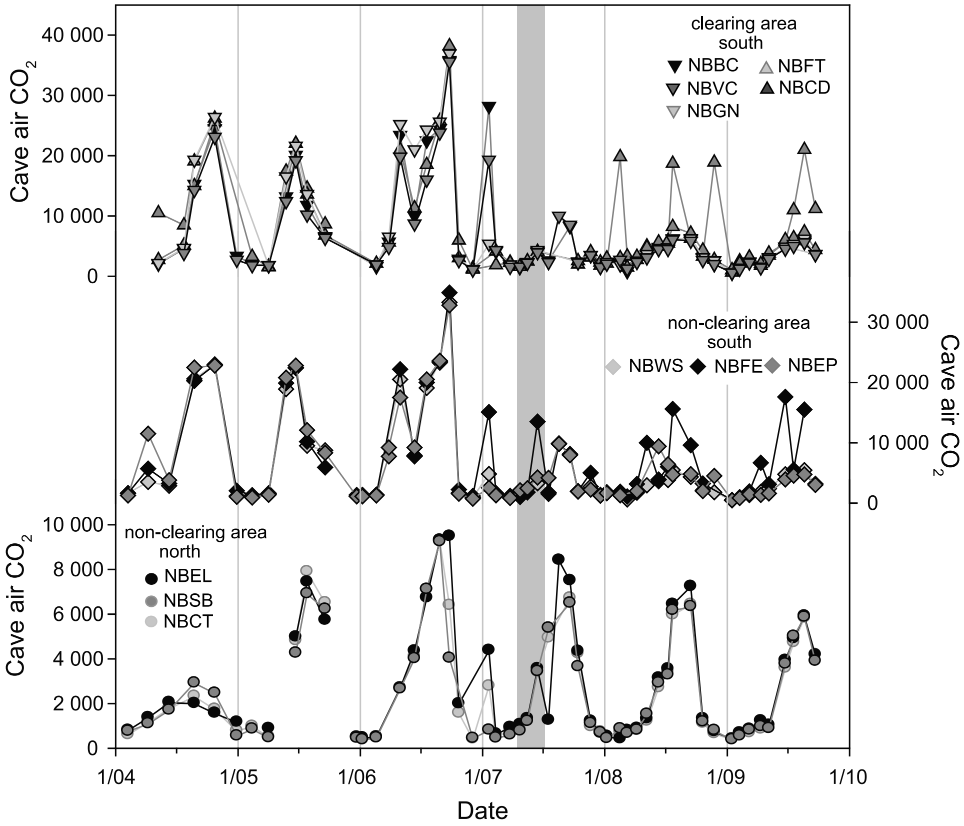

Figure 6. Time series of cave air CO_2 (ppm) are shown. A gray bar delineates the time interval in which brush clearing occurred. Note the varying axis scales.

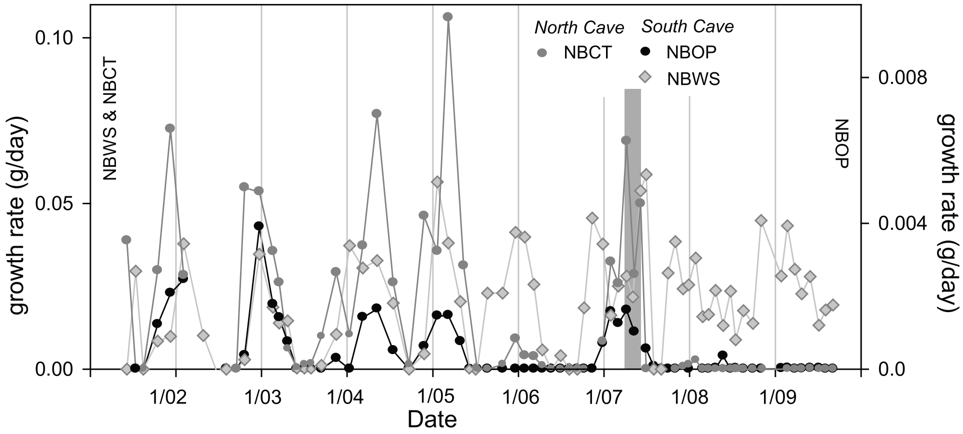

Figure 7. Time series of speleothem calcite growth rates measured by weighing calcite deposits on glass plates are shown. A gray bar delineates the time interval in which brush clearing occurred.

conduit-supplied sites because of additional water in storage. Decreases in postclearing average and maximum drip rates at conduit-supplied sites may be a reflection of dry conditions with small, temporally scattered rain events rather than decreased infiltration related to brush removal.

[25] Nonclearing area sites are located updip from the clearing area and should act as a control to separate the effects of rainfall variability and brush clearing. The inconsistent responses of nonclearing area sites, however, make it difficult to determine what the isolated effect of rainfall variability is on drip rate of clearing area sites. Nonclearing area sites exhibit both significant increases and decreases in drip rate, as well as shifts in maximum drip rate and drip rate variability in several directions (Figure 5). The presence of extreme rainfall variability and the chaotic behavior of drip rate responses of nonclearing area sites make the responses of clearing area sites difficult to interpret in regard to brush clearing. While drip rate characteristics exhibit changes following brush removal, it is not clear whether changes are due to brush removal or temporal variations in rainfall.

3.4. Preclearing and Postclearing Cave Air CO_2

[26] Cave air CO_2 values range from 370 to 9500 ppm in the north cave and 470 to 38,200 ppm in the south cave (Figure 6). Previous work and ongoing research has shown that caves exhibit large fluctuations in cave air CO_2 concentrations that are independent of human visitation [*Banner et al.*, 2007; *Cowan*, 2010]. Average CO_2 values at sites in the south cave, both clearing area and nonclearing area sites, exhibit decreases at all sites postclearing ($p < 0.01$ at seven sites and $p < 0.05$ at one site (Table 3)). Average CO_2 values in the north cave exhibit nonsignificant decreases from pre–brush clearing to post–brush clearing ($p > 0.1$).

3.5. Preclearing and Postclearing Calcite Growth Rate

[27] Plate calcite growth at the three monitored sites ranges from <0.00001 to 0.11 g/d and exhibits distinct seasonality with highest growth rates during winter and little to no growth during summer [*Banner et al.*, 2007]. Little to no calcite growth occurred during the winter 2008 and 2009 at two sites, NBCT (north cave) and NBOP (south cave). NBWS (south cave), however, had calcite growth consistent with previous years throughout these winters. *Banner et al.* [2007] observed this same pattern of severely reduced winter growth in 2006 at NBCT and NBOP relative to previous years, while growth at NBWS remained consistent with previous years.

[28] Calcite growth at NBWS (south) exhibits summer calcite growth inconsistent with summer growth observed in previous years. Calcite growth exhibits a spike immediately following brush clearing (2007), and growth continues at modest rates during the summers of 2008 and 2009. The amount of summer growth in 2007, 2008, and 2009 at NBWS is inconsistent with little to zero growth rates observed during the summers of years previously monitored by *Banner et al.* [2007] (Figure 7).

3.6. Interpreting Brush Clearing Impacts on Cave Air CO_2

[29] Average cave air CO_2 concentrations exhibit a significant decrease at all sites in the south cave following the brush clearing but show no significant change at sites in the north cave (Figure 6). This has several implications related to the dynamics and effects of CO_2 in the subsurface.

[30] 1. The reduction of CO_2 in the south cave at both clearing area and nonclearing area sites suggest that the cave is sufficiently well mixed such that reductions of CO_2 supplied to one portion of the cave affect the atmosphere of the entire cave. The commonly observed high CO_2 values at two south cave sites (NBCD and NBFE, Figure 6), however, demonstrate local heterogeneity, possibly controlled by spatial heterogeneity in fractures and solution-widened conduits through which CO_2 is advecting/diffusing to the cave from the soil zone.

[31] 2. The immediate response of CO_2 to the brush removal suggests that plant root respiration is a significant source of CO_2 to the cave, as opposed to soil microbial activity. The delineation of the contribution of CO_2 from plant root respiration and soil microbial activity is an important aspect of understanding land use and climate change impacts on soil CO_2 dynamics. Previous studies have shown variations in ranges of a 10% to 90% contribution of CO_2 from plant root respiration at various times of the year and a 60% contribution for an entire growing year in nonforest vegetation [*Hanson et al.*, 2000]. On the basis of the reduction of average annual CO_2 concentrations of all

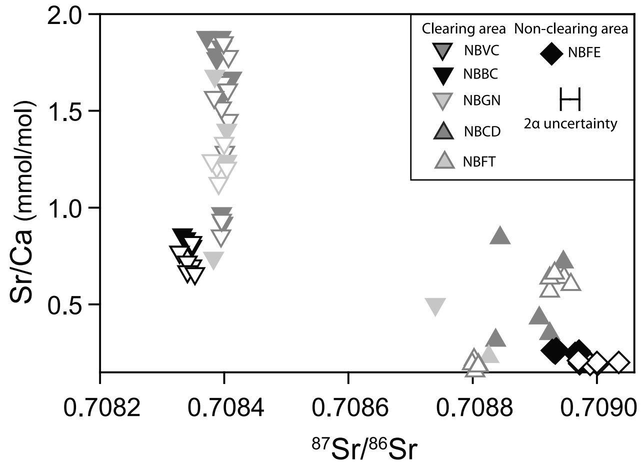

Figure 8. Sr/Ca and $^{87}Sr/^{86}Sr$ values are shown for preclearing (solid symbols) and postclearing (open symbols) intervals.

sites in the south cave, juniper root respiration accounts for 55% of CO_2 delivered to the cave. This result is consistent with experiments that demonstrate a 54% decrease in soil respiration 1 to 2 months after tree girdling eliminated tree root respiration [*Hogberg et al.*, 2001]. Another experimental study, however, documented no changes in soil CO_2 flux following a tree harvest, indicating the root respiration was replaced by accelerated rates of microbial respiration [*Keller et al.*, 2006].

[32] 3. Seasonal density-driven ventilation of cave air CO_2 causes a seasonal growth cycle of cave calcite deposits (speleothems), with fastest growth rates during the winter and slow to zero growth rates during the summer [*Banner et al.*, 2007]. Postclearing reductions in cave air CO_2 have limited the excessive CO_2 build up and allowed calcite precipitation to continue through the 2007, 2008, and 2009 summers at one site, NBWS (Figure 7). A particularly high spike in calcite growth in the summer of 2007 at NBWS may be the result of both increased drip rates resulting from heavy rainfall and reduced CO_2 concentrations. The other two sites, NBCT and NBOP exhibit diminished growth in 2008 and 2009. This may be related to low rainfall conditions that occurred during these years, as a similar degree of reduced growth was observed at these two sites in 2006, another low rainfall year [*Banner et al.*, 2007]. The disruption of the seasonal calcite growth pattern at NBWS due to brush removal has implications for the application of speleothems to reconstruct paleoclimate changes. These results suggest that changes in the presence or absence of seasonal calcite growth lamina in speleothems may be indicative of temporal variations in vegetative cover.

[33] Cave air CO_2 has limited utility in evaluating the impact of brush clearing on recharge but plays a significant role in dictating cave drip water compositions. Drip water precipitates calcite upon outgassing CO_2, making the amount of calcite precipitation dependent on cave air CO_2 concentrations. Calcite precipitation results in an increase in drip water Mg and Sr concentrations relative to Ca, as Ca is preferentially included in the calcite lattice [*Banner and Hanson*, 1990]. Therefore, drip water Mg/Ca and Sr/Ca are dictated by calcite precipitation, which is dependent on cave air CO_2. The impact of reduced cave air CO_2 values on drip water compositions is significant for the interpretation of changes in postclearing cave drip water compositions, as discussed in section 2.2.

3.7. Preclearing and Postclearing Drip Water Compositions

[34] Vadose drip waters are Ca-HCO_3 waters with a total dissolved solids (TDS) range of 168 to 503 ppm and pH of 7 to 8. Drip water exhibits ranges of Ca from 13.9 to 155 ppm, Mg from 1.5 to 33 ppm, Sr from 0.03 to 0.15 ppm, alkalinity from 135 to 417 ppm, Mg/Ca from 0.02 to 2.75 mol/mol, and Sr/Ca from 0.12 to 1.88 mmol/mol. There were no significant differences in drip water Mg, Sr, and alkalinity concentrations preclearing and postclearing. Four of five clearing area sites exhibit decreases in Ca postclearing ($p < 0.05$ at two sites (Table 3)). All the nonclearing area sites (four sites) evaluated for drip water compositions exhibit increases in Ca postclearing ($p < 0.05$ at three sites). Four clearing area sites exhibit increases in Mg/Ca and Sr/Ca ($p < 0.05$ at two sites), and one clearing area site exhibits significant decreases in Mg/Ca and Sr/Ca. Two nonclearing area sites exhibit significant decreases in Mg/Ca and Sr/Ca, and the other two sites do not exhibit change. Drip water $^{87}Sr/^{86}Sr$ values range from 0.70833 to 0.70896 and showed no difference between preclearing and postclearing (Table 3). Drip water $^{87}Sr/^{86}Sr$ values at each site do not vary beyond analytical uncertainty (Figure 8).

3.8. Interpreting Brush Clearing Impact on Drip Water Compositions

[35] Drip water Mg/Ca and Sr/Ca exhibit variability postclearing, but $^{87}Sr/^{86}Sr$ values do not change. Two clearing area sites, which are diffuse supplied, exhibit significant increases in Mg/Ca and Sr/Ca following brush removal (Table 3). A conduit-supplied clearing area site exhibits significant decreases in both Mg/Ca and Sr/Ca. A first-order interpretation of these results might suggest that water flux to diffuse sites decreased, while water flux to the conduit site increased. Mg/Ca and Sr/Ca at the diffuse sites, however, are affected by cave CO_2 concentrations in addition to variable water residence time. Increases in Mg/Ca and Sr/Ca at these sites likely result from decreased CO_2 concentrations as opposed to increased water residence time. In regards to the conduit site, two nonclearing area sites, which are conduit supplied, also exhibit significant decreases in Mg/Ca and Sr/Ca. The decrease in Mg/Ca and Sr/Ca at control sites suggests that rainfall variability may be responsible for the decrease in Mg/Ca and Sr/Ca at clearing area sites. Preclearing and postclearing ranges of $^{87}Sr/^{86}Sr$ values are within analytical uncertainty at all clearing area sites, suggesting that no changes in water residence time occurred (Figure 8). The one nonclearing area site, NBFE, at which Sr isotopes were measured, exhibits a response in $^{87}Sr/^{86}Sr$ values to the heavy summer 2007 rainfall (Figure 4). This demonstrates that $^{87}Sr/^{86}Sr$ values in this system are sensitive to changes in water flux and indicate that constant postclearing $^{87}Sr/^{86}Sr$

values at clearing area sites are indicative of unchanging water flux.

[36] Decreases in drip water Ca concentrations at drip sites with increased postclearing Mg/Ca and Sr/Ca (Table 3) supports that increases in Mg/Ca and Sr/Ca resulted from enhanced calcite precipitation due to postclearing reductions in cave air CO_2. Lower Ca concentrations, however, may also be the result of less CO_2 dissolved in the water causing less dissolution of the carbonate host rock. Limited alkalinity measurements do not exhibit drastic differences between preclearing (254–331 ppm, $n = 2$) and postclearing (225–330 ppm, $n = 6$) but are too few to provide conclusive evidence. Unchanging drip water Mg and Sr concentrations suggest that amounts of carbonate dissolution were unchanged, and modeling of Mg/Ca and Ca and Sr/Ca and Ca covariation (C. Wong, submitted manuscript, 2010) demonstrates that decreasing Ca concentrations can be accounted for by increasing calcite precipitation. If infiltrating water was a significant source of CO_2 to the cave, then decreases in cave air CO_2 concentrations should occur simultaneously with changes in drip water compositions. The unchanging drip water Mg, Sr, and alkalinity concentrations and lower Ca concentrations accountable by calcite precipitation suggest that infiltrating water is not the significant mode of transport of CO_2 to the cave. This result is consistent with an experiment investigating transport of CO_2 into a cave in Spain that concluded advection/diffusion of CO_2 through fractures into the cave was a vastly more significant component than CO_2 degassing from water (I. J. Fairchild, personal communication, 2009). Additionally, advection/diffusion of CO_2 through fractures is more plausible when a significant source of CO_2 is from respiration of tree roots that reach deep (up to 8 m in central Texas [*Jackson et al.*, 1999]) and into fractures and solution-widened conduits.

4. Conclusions and Implications

4.1. Key Results

[37] Brush removal (8000 m^2) was conducted on the Edwards Plateau, above the south cave at Natural Bridge Caverns, which is in the contributing zone of the Edwards aquifer. An assessment of drip rate, drip water compositions, cave air CO_2, and speleothem calcite growth preclearing and postclearing yields the following results. (1) Anomalously high rainfall (700 mm from June to August 2007) was coincident with the conclusion of the brush clearing process. (2) Postclearing changes in drip rate characteristics and drip water Mg/Ca and Sr/Ca are variable at clearing and nonclearing area sites. (3) Preclearing and postclearing ranges of $^{87}Sr/^{86}Sr$ values are within analytical uncertainty at all clearing area sites, while values exhibit preclearing and postclearing variability at nonclearing area sites. (4) Average cave air CO_2 concentrations exhibit significant decreases at seven of nine sites (average difference = 8200 ppm, $n = 9$), clearing and nonclearing, in the south cave following brush removal and exhibit no significant changes in the north cave. (5) The seasonal calcite growth pattern is altered at site NBWS (south cave) as calcite growth continued through the summer, unlike previous years when little to no summer growth occurred.

4.2. Key Inferences

[38] 1. Postclearing changes in drip rate characteristics are too inconsistent and complicated by rainfall variability to support either the hypothesis the brush clearing impacted recharge or the null hypothesis that brush clearing did not impact recharge.

[39] 2. Postclearing increases in drip water Mg/Ca and Sr/Ca beneath the cleared area at diffuse-supplied sites are likely due to enhanced calcite precipitation driven by lower cave air CO_2 concentrations.

[40] 3. Similar preclearing and postclearing $^{87}Sr/^{86}Sr$ values indicate that there is little change in water residence times and suggest that recharge to the cave did not change following the brush clearing.

[41] 4. Immediate decreases in cave air CO_2 concentration following brush removal suggest that live root respiration is a significant source (55%) of CO_2 to the cave.

[42] 5. The reduction of CO_2 to the cave altered seasonal speleothem calcite growth patterns, as summer CO_2 concentrations did not reach such levels as to inhibit calcite growth.

4.3. Key Implications

[43] 1. The effect of brush clearing (reduction of canopy from 83% to 33% over 8000 m^2) on recharge to cave drip sites at 30–60 m depth beneath the cleared area is ambiguous under the time frame and rainfall conditions of this study. The drip water $^{87}Sr/^{86}Sr$ values suggest that brush clearing did not impact recharge, while the drip rate data is too inconsistent to support either that brush clearing impacted recharge or that brush clearing did not impact recharge.

[44] 2. The significant contribution of live root respiration to soil CO_2 production and its sensitivity to changes in vegetative cover should be considered in regard to land and atmosphere coupling processes and understanding feedback loops that may be associated with land use change and climate change.

[45] 3. Temporal changes in overlying vegetation may be reflected in changes in speleothem growth rates and periodicity.

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