Removing woody vegetation has little effect on conduit flow recharge

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ABSTRACT

In drylands across the globe, grasslands and savannas have succumbed to encroachment by woody plants. There is a concern that, in some cases, these changes may lead to lower groundwater recharge and streamflow. In karst landscapes, the effect of woody plants on recharge is difficult to determine because of the shallow and rocky soils. In our study, we estimated the amount of water entering a shallow cave (3–5 m deep) as a surrogate measurement for groundwater recharge, to evaluate whether the removal of Ashe juniper (Juniperus ashei) above the cave would affect recharge. Three sets of large-scale rainfall simulations were conducted in 2005, before removal of the overstory juniper; seven were conducted in 2008, soon after the juniper were removed; and two were conducted in 2009, one year after juniper removal. We found that recharge occurred mainly via conduits or macropores and, as such, was extremely dynamic and responsive to rainfall. The amount of recharge ranged from 3% to 17% of the water applied, the higher percentages being measured when antecedent soil conditions were wet. At least in this case of recharge taking place via conduit flow, removal of the juniper had little if any effect. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS recharge; woody plant encroachment; karst; cave hydrology; juniper

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INTRODUCTION

Across the globe, woodlands have expanded at the expense of grasslands and savannas in a process often described as woody plant encroachment. The ecohydrological implications of this vegetation shift are of considerable importance, especially in this era of increasing demand for water (Archer et al., 2011; Wilcox et al., 2011), and ultimately depend on a number of factors – including climate, soils, geology and depth to groundwater (Huxman et al., 2005; Wilcox et al., 2006). Whether or not reducing the coverage of woody plants may appreciably increase groundwater recharge is an important question, especially for dryland areas (Huxman et al., 2005; Wilcox et al., 2006).

In the Edwards Plateau region of central Texas, an extensive area underlain by karst bedrock, woody plants have come to dominate in the last 100 years (Diamond and True, 2008). The growing demand for water in the region has led some to speculate that ‘brush control’ – to reduce woody plant cover – could increase water supply. As a result, considerable interest has been generated in determining whether and to what extent groundwater recharge and streamflow might be augmented through control of woody vegetation, primarily Ashe juniper (Juniperus ashei) (Wilcox and Thurow, 2006). Answering this question is difficult, however, because the hydrology of karst terrain is inherently complex.

In the last decade, our understanding of how trees and shrubs may alter the water cycle in karst regions has been significantly advanced by a suite of studies employing different approaches and focusing on different aspects of the water cycle. These studies include investigations of evapotranspiration measured by flux towers (Heilman et al., 2009; Banta and Slattery, 2011); soil–water and plant–water dynamics (Dasgupta et al., 2006; Schwinning, 2008); interception (Owens et al., 2006); runoff generation (Taucer et al., 2008; Wilcox et al., 2008b); geochemistry of springs water (Musgrove et al., 2010); and water budgets at both the small-catchment (Wilcox et al., 2005; Huang et al., 2006) and large-catchment scales (Wilcox et al., 2008a; Wilcox and Huang, 2010). Collectively, the results of these and earlier studies indicate that annual evaporation is 35–85 mm higher in woodlands than in grasslands (Dugas et al., 1998; Heilman et al., 2009; Banta and Slattery, 2011) and that brush control could augment springflows to a similar degree (Huang et al., 2006). However, where springs are not present, brush control has little if any effect on streamflows (Wilcox et al., 2005; Banta and Slattery, 2011).

Paradoxically, long-term streamflow records from the region strongly indicate that baseflows (that portion of streamflow provided by springs and groundwater) have increased even as woody plant cover has increased (Wilcox et al., 2008a; Wilcox and Huang, 2010). The likely explanation for this is that the condition of the land has improved as a result of declining grazing pressure. These combined findings suggest that water budgets may be...
affected by changes in woody plant cover but, at large scales, other factors – such as overgrazing – can override those effects.

With respect to recharge, it remains to be determined whether and to what extent woody plant cover plays a role. Water balance data, from the evapotranspiration studies cited earlier, suggest that as woody plant cover increases, the higher evapotranspiration must translate to decreased recharge. But this conclusion has yet to be independently verified. And doing so is especially vexing in karst environments, where it is difficult to directly measure recharge: The water travels through the shallow, rocky soils mainly via discrete pathways such as fissures, fractures and relatively large macropores. For this reason, various researchers devised an approach whereby recharge in karst landscapes can be directly measured: by monitoring drip rates in natural caves (Ayalon et al., 1998; Baker and Brunsdon, 2003; Arbel et al., 2010). This was the approach used by Wong and Banner (2010) in the Edwards Plateau region of central Texas; they monitored relatively small cave drips in the Natural Bridge Caverns, before and after woody plant removal. But their study findings failed to demonstrate that changes in drip rates or geochemistry could be attributed to brush removal.

Our understanding of recharge dynamics in karst landscapes has been enhanced by Gregory et al. (2009), who used simulated rainfall to monitor cave recharge in the Edwards Plateau. They found that recharge in these landscapes is very dynamic, in their study accounting for between 7% and 17% of the water applied. Recharge typically reached its maximum level within 20 min of rainfall cessation and declined rapidly thereafter.

In this paper, we report on our work, which continues that of Gregory et al. (2009). At the same site, we first removed the Ashe juniper growing on the area overlying the cave and then conducted comparable rainfall simulation experiments. Our objective was to determine whether and to what extent the removal of woody vegetation would alter the amount and timing of recharge. On the basis of past research (Dugas et al., 1998; Huang et al., 2006; Wilcox et al., 2006), we hypothesized that recharge in the cave would, in general, be higher following removal of Ashe juniper. Possible mechanisms leading to higher recharge would be generally wetter soils because of lower plant transpiration and lower interception loss.

The climate of this region is semiarid to subhumid and exhibits a strong precipitation gradient, with averages ranging from 850 mm year⁻¹ in the east to 400 mm year⁻¹ in the west. Annual precipitation in the San Antonio area averages about 738 mm year⁻¹, varying from 257 to 1328 mm in individual years. Over the last 100 years, most of the once-extensive savannas and grasslands in the region have converted to juniper and oak woodlands.

In 2008 and 2009, we carried out rainfall simulation experiments (after removal of the juniper) on an area overlying a shallow cave, Bunny Hole, located within the recharge zone of the Edwards Aquifer (Figure 1). The experimental protocol was identical to that used at this site in 2005, before removal of the juniper (Gregory et al., 2009). The cave lies 3–5 m below the surface and consists of a maze of passages that extends 198 m in length and reaches a maximum depth of 5 m below the entrance. Soils are classified as Tarrant–Brackett association (Taylor et al., 1962), which typically are very rocky with a highly organic A horizon (0–30 cm) overlain by a weathered caliche horizon (Wilcox et al., 2007).

Before removal of woody plants in 2008, the area overlying the cave was a mature Ashe juniper (Juniperus ashei) and live oak (Quercus fusiformis) woodland. Rocky outcroppings, bare soil and leaf litter make up a significant portion of the ground surface. There are scattered agarita (Berberis trifoliolata) and netleaf hackberry (Celtis reticulata), as well as sparse grass and other herbaceous cover.

METHODS

As described in Gregory et al. (2009), their work in 2005 began with irrigation experiments to determine the area over the cave that contributes to recharge. These experiments found a contributing area for recharge of approximately 22 × 16.5 m (Figure 1). They also indicated that water enters the cave ceiling at four main locations.

Vegetation removal and surveys

In February 2008, we hand-removed all the juniper – a total of 45 trees, 22 of which were within the contributing area. Trees were cut as close to the ground as possible, and the remaining stumps were left in place. The oaks (about 10 small-to-moderate size trees) were left in place (Figure 2). Removing juniper and leaving oaks in place is a common practice in the area; oaks are, in general, viewed quite favourably and actually enhance property values.

Ground vegetation cover was estimated via the point-intercept method (Mueller-Dombois and Ellenberg, 1974), first in April 2008 (a few months after the juniper were removed) and then in July 2009. In both instances, data were collected from 20 transects evenly spaced across the contributing area, for a total of 1539 points. Areal and basal cover were determined at points spaced 30 cm apart on each transect.
Rainfall simulation

The rainfall simulator described by Munster et al. (2006) was used for the studies at this site; having the capability to apply water above tree canopies, this device was designed to simulate rainfall at the hillslope scale. It consists of six telescoping masts distributed over the contributing area. Each mast has a maximum extension of 11 m and is topped with a manifold that feeds four upward-facing sprinkler heads. The median raindrop size is about 2 mm, varying slightly with application rate (Munster et al., 2006). A flow meter controls the volume of water pumped to the sprinkler heads.

We carried out nine sets of rainfall simulation experiments over the surface of the cave in 2008 and 2009. The area wetted during these simulations (application area) was estimated at around 26 × 20 m. Like the standard simulations of Gregory et al. (2009), our standard simulations consisted of three runs of varying durations and application rates: Run 1 lasted 1 h at a rate of about 21 mm h⁻¹; Run 2 lasted 2 h at a rate of 6 mm h⁻¹; and Run 3 lasted 45 min at a rate of 28 mm h⁻¹. The three runs were
separated by about 30 min. In total, we applied around 54 mm of water over 5 h.

Cave recharge

As explained by Gregory et al. (2009), cave recharge was defined as water entering the cave through fractures or cracks in the cave ceiling (whether from natural or simulated rainfall). To monitor this recharge, dripwater collectors were installed at each of the four main water-entry locations identified by the 2005 irrigation experiments. Each collector consisted of a 0.5- to 1.5-m-long frame constructed from 19-mm polyvinyl chloride covered by polyethylene sheeting (Figure 3A). The water captured by this collector was routed, via polyvinyl chloride pipe connected to a funnel, into a custom-made, 1-litre tipping bucket mounted on a pivot of stainless steel to keep it from rusting in the humid cave environment (Figure 3B). The number of tips were recorded and transmitted to a datalogger on the surface. These four dripwater collectors captured about 60% of the water that entered the cave through the ceiling (Gregory et al., 2009).

Throughfall, stemflow, and interception

Throughfall (the amount of water landing on the surface) was measured manually, by means of 72 plastic rain gauges evenly spaced on a 16.5 × 24 m area above the cave. Stemflow was measured only for the period before the juniper trees were removed (see Gregory et al. [2009] for details).

Although we controlled the volume of water applied for the post-juniper-removal experiments, the exact extent of the application area could not be determined because of varying amounts of wind drift. We were careful to carry out simulations on days when the wind was light, but even so, some wind drift is inevitable. As noted, we estimated the application area to be about 20 × 26 m. This size estimate, along with the volume of water applied, allows us to calculate the average depth of the water applied. Then, with the detailed measurements of throughfall, we can estimate how much of the applied water is lost through interception by trees (and drift loss via wind), as the difference between the amount of water applied and the amount of throughfall and stemflow.

Surface runoff

Surface runoff was captured at the downslope end of the application area. Gutters were installed to route water to 15.24-cm H-flumes equipped with a WL700-001 Ultrasonic Water Level Sensor (Global Water, Gold River, CA). For the experiments conducted before juniper removal (Gregory et al., 2009), one set of collections was sufficient; but surface runoff patterns changed after tree removal, and a second runoff-collection system was installed at the east end of the application area.

RESULTS

Vegetation

Cutting and removal of the Ashe juniper changed the surface over Bunny Hole Cave in a fundamental way: The almost complete canopy that had covered the cave was reduced to about 10 small-to-moderate – size oak trees. We estimate that the total remaining canopy cover was around 30%.

Areal and basal ground-cover data for April 2008 and July 2009 are summarized in Table I. In the year following tree removal, areal herbaceous cover increased from around 20% to 30%, and bare ground declined from about 8% to 1%.
Rainfall simulation experiments

A total of 12 comparable sets of rainfall simulation experiments were conducted at Bunny Hole Cave in 2005, 2008 and 2009—three before juniper removal (pre-removal) and nine afterwards (post-removal). Rainfall distribution was affected by both wind drift and by the remaining oak trees that were on the site. In general, higher rainfall volumes were applied towards the middle of the plot. This was particularly true for the first and the last runs, which were higher intensity applications (Figure 4). The results of the pre-removal simulations are summarized in the following sections to facilitate comparison of pre-removal and post-removal conditions (Table II a and b).

Interception. As would be expected, interception (estimated as (R-S-T)) was higher for the period before juniper removal than after. For the pre-removal period, we found that under dry conditions, about 20% of the water applied was lost; this percentage decreased as conditions became wetter (Table IIa). For example, during the second standard simulation (14 July 2005), which took place 24 h after the first standard simulation, interception made up around 15% of the total water applied. Conditions were the wettest and coolest during the third standard simulation (28 July 2005). Over the preceding 2 weeks, about 50 mm of natural rainfall had occurred, 11 mm of which fell in the 5 h just before the start of the simulation. Equally important, it was cloudy during the simulation, which most certainly reduced evaporation. As a result, virtually no interception was measured during the third simulation. For the post-removal period, the loss factor was smaller, ranging from 0% to 12% (Table IIb). This loss could still be attributed partially to interception (by the oak trees remaining on the site, which covered about 30% of the area over the cave) and partially to wind drift. For some simulations, the amount of water in the throughfall collectors was greater than the amount of water applied. This suggests that the application area during those simulations was slightly larger than estimated.

Stemflow. Stemflow was measured only during the pre-removal period. It accounted for between 4% and 8% of the water reaching the ground surface and was highest under the wettest conditions (Table IIa).

Cave recharge. On average, the cave recharge measured accounted for between 3% and 17% of the water applied. For some individual runs, recharge was as high as 24% and—as would be expected—increased as conditions became wetter. There were no obvious differences between the pre-removal and post-removal periods in spite of the fact that effective precipitation was generally higher in the post-removal period because of reduced interception losses. As highlighted in Figure 5, the most obvious difference in recharge could be attributed to antecedent soil moisture conditions: recharge was highest under wet conditions. Four of the standard simulation sets were performed
Table IIa. Water budget (mm) for the pre-removal experiments (Gregory et al. 2009). Each simulation consisted of three sequential runs. Total rainfall (R) is calculated as the application volume divided by the application area. An estimate of interception is obtained from the difference between R and the amount of water arriving at the surface (stemflow and throughfall) (R–S–T). Obviously, instances showing T greater than R reflect some measurement error – most likely in the size of the application area (which was affected by the extent of wind drift during the experiment).

<table>
<thead>
<tr>
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<th>Run 1</th>
<th>Run 2</th>
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<th>Total</th>
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<th>Total</th>
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<td>11.4</td>
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<td>0.9</td>
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<td>0.5</td>
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<td>1.6</td>
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back-to-back, that is, rainfall was applied on sequential days (13 and 14 July 2005; 18 and 19 June 2008; 29–31 July 2008; and 3 and 4 June 2009). Recharge was always highest on the second day of simulations. On the one occasion when simulations were performed 3 days in a row, the difference between days 2 and 3 was not great (Figure 5).

The ephemeral nature of cave recharge is evident from the event hydrographs (Figure 6). Recharge began and ended within minutes of the beginning and ending of rainfall simulations, demonstrating direct pathways from the ground surface to the cave some 3–5 m below. There was a lag of 15–20 min between cessation of the rainfall event and peak cave recharge, taken as the integrated time needed for water to move from the surface to the cave ceiling.

Surface runoff. Although remaining a relatively small component of the water budget, surface runoff increased from about 3% of the pre-removal water budget to as much as 10% of the post-removal water budget (Table IIb, Figure 5). Surface runoff was highest during the third runs of the standard simulations, which were conducted at higher intensities than the other runs (and during which conditions were already the wettest).

DISCUSSION AND CONCLUSION

A generalized ecophysiological theory – or expectation – is that all other conditions being equal, groundwater recharge will be lower for a woodland or forest than for a grassland (Satterlund and Adams, 1992; Zhang et al., 2001, National Academy of Sciences, 2008). The main reason for this expectation is that evapotranspiration in woodlands is greater than in grasslands. A body of research performed on the Edwards Plateau indicates that this should be the case (Wilcox et al., 2006). In other words, we would expect groundwater recharge to increase following removal of Ashe juniper because lower evapotranspiration and interception loss following tree removal should mean that soil moisture will, in general, be higher; therefore, when rainfall does occur, less water would be required for soil storage and more recharge would occur.

Contrary to this expectation, our results suggest that in cases where groundwater recharge occurs mainly via conduit flow – as it often does in karst systems – removal of woody plants has little effect on recharge. The post-removal recharge rates we measured via cave drips were comparable with the pre-removal rates, in spite of the fact that interception loss was lower, and therefore the ‘effective precipitation’ (the amount of water that makes it to the ground surface, as measured by the network of rain gauges on the ground) was greater. In other words, the interception savings (which ranged from 1 to 12 mm/simulation) did not translate to higher amounts of recharge. Recharge is apparently not sensitive to these relatively small amounts of water.

Much of the water that we applied was not accounted for in that it was not recharge or surface runoff. Water that was not accounted for did enter the soil and most likely remained stored in the soil or perhaps the underlying limestone. Another but more remote possibility is that some water may have exited the application area via lateral subsurface flow (Wilcox et al., 2008b).

Similarly to our study, Wong and Banner’s findings (2010) were similar to ours: little difference in drip rates before and after juniper removal (however, because the drip volumes they measured were relatively small, they were unable to make a definitive conclusion). The strength of our study is that we were able to measure comparatively large volumes of water flowing into the cave. In addition, we made multiple measurements during comparable storms, which increases the level of confidence in our results. In summary, we found that the presence or absence of trees has little effect on conduit recharge, which we found to be exceedingly rapid – with response times literally minutes after the initiation of rainfall. Because of this rapid response time, conduit recharge appears to be decoupled from the much slower changes in evapotranspiration dynamics that follow tree removal.
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**Table IIb. Water budget (mm) for post-cut experiments.**

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Figure 5. Runoff and recharge for pre-removal and post-removal conditions. The darker blue bars represent simulations that followed a prior simulation by one day and, as such, represent wet antecedent conditions. No runoff was measured for 12–19 June 2008 because the second runoff collector had not been installed.

Figure 6. Runoff and recharge for selected rainfall simulations for pre-removal and post-removal conditions. Each simulation consisted of three runs of varying durations and application rates: Run 1 lasted 1 h at a rate of about 21.1 mm h$^{-1}$; Run 2 lasted 2 h at a rate of 5.8 mm h$^{-1}$; and Run 3 lasted 45 min at a rate of 27.5 mm h$^{-1}$. The three runs were separated by about 30 min.
EFFECT OF SHRUB REMOVAL ON CAVE RECHARGE

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REFERENCES


