Brush Management for Improved Water Yield in Karst Landscapes

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Abstract

Most karst landscapes allow rapid groundwater recharge and are therefore important for maintenance of water supply. Where grasslands, including those in karst landscapes, have converted to shrubland or woodland, reduction of woody canopy cover via grassland restoration is often implemented to mitigate current and future water shortages. The science is generally in agreement that reduction of canopy cover increases water yield in most systems; however, various aspects of existing scientific literature are fueling a debate that questions the efficacy of brush management for water supply as public policy. We analyzed the literature from across the world and also from the karstic Edwards Plateau in the US to formulate a more nuanced understanding of the canopy cover-water yield relationship, especially in karst systems. We believe that brush management can improve water supplies in karst systems and we recommend basic principles for effective implementation of brush management as public policy.

Keywords: water yield, brush management, grassland, karst, recharge

Introduction

Karst landscapes - characterized by soluble rock whose dissolution creates landscape features such as caves, sinkholes, and sinking streams (Gillieson 1996) - make up roughly 10% of the Earth's land area and supply drinking water to almost a quarter of the world's human population (Ford and Williams 2007). High rates of groundwater recharge and the formation of highly productive aquifers makes karst areas important for water supply (Hauwert and Sharp 2014).

Currently two-thirds of the world's population faces severe water scarcity for at least one month per year (Mekonnen and Hoekstra 2016). To address current and forecast water shortages, governments and private organizations throughout the world have established programs to conserve and manage ecosystems for the provision of water supply (Ex. South Africa; Sub-Saharan Africa; South America; New Zealand; New York, USA; Texas, USA; and others). Many such programs in grassland biomes use brush management to maintain or improve water yield (the sum of runoff and groundwater recharge) while preserving water quality (Le Maitre et al. 2002, Mark and Dickinson 2008, TSSWCB 2014).

However, debate has emerged in recent years as to the utility of brush management for water yield. For example, during the public comment period of the Texas State Water Supply Enhancement Plan, a group of researchers offered written comment that "…brush management will NOT increase water yields" (original emphasis) (Wilcox et al. 2014) despite experimental evidence to the contrary (Table 1). In contrast, a respected practitioner commented, "…it [brush management] will work – but only with a great series of negative side effects" such as increased erosion, loss of land value, increased flooding, and reduced water quality (Nelle 2014) though this concern seems to relate more to the method of brush removal than the change in vegetation type.

Here we provide an analysis of the effect of brush management on water yield in karst systems with the goal of informing land management as well as water policy. We focus on the karst landscape of the Edwards Plateau in central Texas because of its position at the junction of debate and water policy.

We begin with a brief overview of some of the important reviews that have been conducted on the subject from across the world   These papers are not karst-specific, but do help to establish the nature of the relationship between woody cover and water yield as it has been observed in most systems. These papers also identify some situations in which the relationship seems to break down. We then move to the regional scale where we use the global perspective to interpret the type of uncertainty and disagreement that often emerge among papers within a common area of study. We conclude by exploring several recurring themes seen throughout the literature in order to help build a more nuanced understanding of the relationship between vegetation and water yield.

Methods

Literature search

Material that was not already in our possession was acquired via academic search engines including Google Scholar and JSTOR, and ISI Web of Science or directly from authors or agencies. We focused our search on literature survey papers that compiled large data sets across a broad range of environmental conditions as well as on regionally-specific (Edwards Plateau) studies that quantified the entire water balance (precipitation, evapotranspiration (ET) (the sum of evaporation and transpiration), runoff, and recharge) within paired catchments or within treated catchments in which adequate pre-treatment data had been gathered. Other papers that quantified only a portion of the water balance (only precipitation and runoff, for example) or that focused on physiological processes (such as plant water use efficiency) were used supplementally to illustrate mechanisms of hydrology or system water use.

Study area

The karstic Edwards Plateau in central Texas, USA (Figure 1) recharges the Trinity and Edwards aquifers as well as other minor aquifers. The Edwards aquifer alone supplies drinking water to more than 1.7 million people in and around the cities of San Antonio and Austin (GEAA 2016). Soils are primarily mollisols which are typically formed by grassland vegetation. Other soils include alfisols and inceptisols. Pre-European settlement vegetation was likely a mix of mixed-grass prairies and woodlands of Ashe juniper (*Juniperus asheii*) and live oak (*Quercus fusiformis*) (Schmidly 2002). Woody cover has likely increased since European settlement due to a host of factors including fire suppression and overgrazing (Van Auken 2000).

Literature Review

The Global Context

By the late 1970's, it was well-understood in some areas, such as the UK (Calder 2002), that afforestation (increasing forest cover) of upland areas generally reduced runoff. Since the early 1980's, literature reviews of canopy cover and water yield from around the world (Bosch and Hewlett 1982, Brown et al. 2005, Calder 2002, Davie and Fahey 2005, Farley et al. 2005, Hamilton 2008, Jackson et al. 2005, Le Maitre et al. 1999, McVicar et al. 2007, Stednick 1996, Zhang et al. 2001) have found strong evidence that the relationship is inverse (decreasing water yield with increasing canopy cover and vice versa) across many biomes. Further, these reviews encountered very few cases in which the relationship was positive (increased water yield with increased canopy cover and vise versa). For example, (Hamilton 2008) states that "the assumption that more trees equals more water is based on incorrect understanding of the hydrologic cycle. Tree canopies reduce groundwater and streamflow through interception of precipitation and evaporation and transpiration from foliage."

The inverse relationship between tree cover and water yield, however, does not seem to hold in all circumstances. In cloud forests, cloud-water condensation on leaves can contribute to soil water, so in this case canopy cover and water yield may be positively related (Calder 2000, 2002, Hamilton 2008). In more arid systems such as pinyon-juniper woodlands of the southwestern US water yield is largely minimal or unaffected by changes in woody cover (Clary et al. 1974, Collings and Myrick 1966, Ffolliott and Stropki 2008, Myrick 1971, Zou et al. 2010). Similarly, in semi-arid mesquite savannas of south Texas, minimal additional water yield from brush removal (Carlson et al. 1990, Weltz and Blackburn 1995) may not justify the cost of implementation. These field studies align with Zhang et al. (2001) who found that even proportional improvement in water yield from canopy reduction is much reduced below about 500mm of annual precipitation, likely because potential ET far outstrips precipitation. There may also be little opportunity for increased water yield in these systems due to soils or geology that restrict deep drainage (Ffolliott and Stropki 2008, Wilcox et al. 2006b). Abundant herbaceous growth after canopy removal may also increase ET rates (Carlson et al. 1990, Guardiola-Claramonte et al. 2011, Nolan et al. 2015).

Regional Research

Dugas et al. (1998) analyzed the results of brush removal from paired watersheds at Seco Creek near San Antonio, TX. All juniper taller than 0.5m within the treatment plot were cut. ET in the treated watershed decreased substantially during the first two years after treatment but returned to pre-treatment levels during the third year post-treatment. Average ET reduction in the treated watershed throughout the three-year post-treatment period was 0.07 mm/day or about 3.8% of annual rainfall.

The authors postulate that ET in the treated plot returned to pre-treatment levels in the third year post-treatment because of abundant growth of herbaceous plants released from competition. The first two years after treatment, however, were the two driest years of the five-year study period while the third year post-treatment received 113% of average annual rainfall. This may have also contributed to the drop in ET difference between treated and untreated plots. As mentioned in the discussion, the largest proportional water yield differences are often seen after small storms and in dry years.

Wu et al. (2001) used GIS analysis and the SPUR-91 hydrologic model to generate woody cover-to-ET curves for the dominant range sites in the Cusenbary Draw basin near Sonora, TX. Consistently inverse and non-linear relationships are predicted for five range sites. On range sites with shallow soils, water yield is predicted to increase dramatically below about 20% woody cover. On range sites with deep soils, however, water yield is predicted to respond relatively weakly to changes in woody cover.

Wu et al. (2001) also found that although basin-wide woody cover remained effectively unchanged from 1955 to 1990, its spatial arrangement changed significantly, likely as a result of preferential brush removal on the most productive rangeland while woody cover increased on the least productive rangeland. The SPUR-91 model predicted that this change in woody cover distribution would increase water yield at the basin scale because of a threshold of woody cover at around 20%, above which simulated ET approximately levels off at its highest rate.

At a site near Uvalde, TX, Wilcox et al. (2005) found that runoff did not respond to any level of canopy removal (100% or 70%). However, Wilcox et al. (2005) did not estimate ET or recharge.

Huang et al. (2006) analyzed the hydrologic effects of Ashe juniper removal within a 19-ha catchment at the Honey Creek State Natural Area near San Antonio, TX. After monitoring streamflow for two years, juniper in about 60% of the treatment catchment was cut with tree shears. During a two-year post-treatment period, they found that mean runoff per rain event increased 60%. Significant differences in runoff volume were detected only for non-summer rain events, however, potentially because high-intensity, short duration rain events which can reduce the effect of vegetation type on hydrology are more common during the summer. Overall, the authors estimate that the juniper removal treatment increased streamflow by about 46 mm annually, representing 5% of precipitation.

Bazan et al. (2013) investigated the effects of Ashe juniper removal on the water balance within a small test plot above Bunny Hole Cave near San Antonio, TX. Pre-treatment vegetation above the cave was full-canopy oak-juniper woodland. Treatment removed all juniper trees, leaving ten small-to-moderate-sized live oaks with a canopy cover of about 30%. Three sets of rainfall simulations were conducted pre-treatment and nine post-treatment. Under dry conditions, pre-treatment canopy interception was about 20% while post-treatment interception ranged from 0% to 12%.

Cave recharge - “water entering the cave through fractures or cracks in the cave ceiling” (Bazan et al. 2013) - was used as a proxy for total recharge in the research area. Cave recharge remained unchanged post-treatment, however, surface runoff increased from “about 3% of the pre-removal water budget to as much as 10% of the post-removal water budget” Bazan et al. (2013).

A challenge to the inverse canopy cover-water yield relationship in central Texas is presented by Wilcox and Huang (2010). This paper has been fairly influential in the regional brush control debate, so we give it more than proportional consideration here. The authors analyzed streamflow data for the major rivers of the Edwards Plateau for which data are available from at least 1925: the Upper Llano, Nueces, Frio, and Guadalupe (Figure 3). Although neither precipitation nor stormflow changed significantly during this time, baseflow, on balance, increased. The authors assert that reduced grazing pressure along with a dramatic increase in woody cover since 1960 have improved the infiltration capacity of soils and thereby increased baseflow.

Using data from Walker et al. (2005) and Smeins et al. (1997), Wilcox and Huang (2010) demonstrate a substantial decline in the number of grazing animal units on the Edwards Plateau since the 1940’s, indicating that herbaceous cover along with soil infiltration rate likely improved. The authors, however, do not validate their hypothesis of rangeland degradation followed by woody encroachment beginning in about 1960 (for example, by original analysis or by citation of peer-reviewed studies). The paper, therefore, confirms only one half of its proposed cause and effect relationship, leaving us to proceed under the potentially false assumption that brush encroachment has been occurring in the study area since 1960.

Other resources indicate that although woody cover has increased across much of the Edwards Plateau since European settlement, woody encroachment was likely well underway by the end of the 19th century (Bray 1904, Richardson 1873, Schmidly 2002) and already largely completed by the mid-20th century (LCRA 2000, Wu et al. 2001). For example, based on first-hand accounts, woody cover in the Pedernales River basin, south of the Llano River basin on the Edwards Plateau, is likely no more extensive today than it was during the latter part of the 19th century (LCRA 2000). Using GIS analysis of aerial photos, Murray et al. (2013) found that between 1937 and 2004, the area of woody vegetation on the Balcones Canyonlands National Wildlife Refuge in the Colorado River basin changed minimally, from 62.0 to 64.2%. Using GIS analysis of aerial photography, Wu et al. (2001) found that the basin-wide woody cover of the Cusernary Draw catchment just west of the Llano River basin “remained virtually unchanged” from 1955 to 1990.

As stated earlier, Wu et al. (2001) found that, although basin-wide canopy coverage remained unchanged, its arrangement became more heterogeneous, which would have in isolation worked to increase water yield. Data from the 1987 Texas State Brush Control Plan (TSSWCB 1987) (Figure 4) indicate expanding brush control efforts statewide between about 1950 and 1970 which suggests woody cover in the basins studied by Wilcox and Huang (2010) may have been reduced and/or become more heterogeneous during that time. Additionally, although not clearly causal, the similarity in the patterns of brush control change in Figure 4 and the change in streamflow in Figure 3 is notable. The area of brush control statewide as well as streamflow both decline until about the early 1950’s, then increase until the early 1970’s.

Ultimately, Wilcox and Huang (2010) make a valuable observation that, contrary to popular belief, streamflow in the basins increased during the second half of the 20th century, predominately via improved baseflow. It is also notable that the increase in baseflow did not come at the expense of reduced stormflow. However, the proposal that increased canopy cover was a causal mechanism of increased water yield does not fit with the overwhelming majority of other studies on the subject throughout the world. The concept of afforestation improving baseflow via reduction of runoff is often parlayed in common discourse, and it makes hydrologic sense when the landscape that is afforested has been severely degraded. Reduced dry season flows after tropical forest clearing and subsequent degradation by agriculture and impervious cover have been documented extensively in the tropics (Bruijnzeel 2004). However, when soil characteristics are maintained to allow continued infiltration of rainfall, then baseflow is typically improved and runoff reduced (Bruijnzeel 2004). We believe, therefore, that a more likely explanation for the hydrologic changes documented by Wilcox and Huang (2010) is that canopy cover has actually decreased in the river basins studied or at least become more heterogeneous during the study period while at the same time recovery of herbaceous biomass has improved hydrologic soil processes. Obviously, our hypothesis needs to be validated by GIS analysis of canopy cover change in the region during the 20th century.

Banta and Slattery (2011) analyzed the results of one of the longest-duration and largest-scale experiments on the effects of Ashe juniper removal on water yield. A 223-ac control watershed as well as an adjacent similarly-wooded 340-ac treatment watershed at the Honey Creek State Natural Area were each instrumented to record rainfall, streamflow volume and quality, as well as ET.

Pre-treatment hydrologic data were collected for three years. During the fourth year of the study approximately 70% of the Ashe juniper in the treatment watershed was cut and left in place. Post-treatment hydrologic data were collected for six years. Streamflow volume in the treatment watershed was not significantly changed but total suspended solids (TSS) was reduced. ET was also reduced by the equivalent of approximately 8% of annual rainfall in the treatment watershed, resulting in an effective 48% increase in groundwater recharge equivalent to 8% of annual precipitation.

Discussion

Research from across the globe demonstrates that in most cases the correlation between woody cover and water yield is inverse, meaning that afforestation tends to decrease water yield while canopy reduction tends to increase water yield. Additionally, research from the Edwards Plateau also demonstrates that the relationship holds for this area and that water yield can be improved via reduction of canopy cover. However, in response to prior predictions of water yield gain that were overly optimistic, as in the case of the North Concho River project, the pendulum of scientific opinion seems to be swinging in the opposite direction. Further, despite general agreement among numerous field and modeling studies, in cases where experimental data related to a particular subsystem process are inconsistent with system-level function, some researchers seem inclined to throw the baby out with the bathwater, that is, to discount the entire inverse canopy cover-water yield paradigm.

By contrast, we see that recent research expands our understanding of the limitations of canopy manipulation to impact water yields. Apparently dissimilar findings by various research teams do not, in our view, prove or disprove an entire framework of hydrology. Instead, they offer opportunities to address previously unanswered questions. The influence of canopy cover is nested among and comprised of a multitude of factors that offset or augment its overall effect on water yield. It is scarcely plausible that canopy cover is the dominant factor influencing water yield across every temporal and spatial scale, therefore in many cases prudent brush removal may only improve water yield marginally. However, for a land management or policy decision to be a sound one, it does not need to exert a dominant influence on the system under all conditions; it just needs to influence the system adequately enough to justify its cost.

In examining the literature as a coherent body, we see the development of certain patterns and themes that allow for more nuanced understanding. Below, we explore several of these themes.

Curvilinear Relationship Between Cover and Yield

Understanding the nature of the canopy cover-water yield relationship is important for planning the extent of brush control treatments. Thurow postulated that the relationship was exponential, that there is little change in water yield from complete cover to about 15% but a rapid rise in water yield from 15% cover to 0% (Thurow 1998). His explanation is that following brush control the remaining trees expand their root systems to take up additional water. In the Rocky Mountain region, Troendle (1987) found an exponential relationship between daily ET per leaf area and basal area. As stand-level basal area is reduced (and available water is increased), transpiration per leaf area increases exponentially. Asbjornsen et al. (2007) found that burr oaks (*Quercus macrocarpa*) in a restored savanna displayed higher tree-level transpiration than burr oaks in a nearby woodland encroached by elms (*Ulmus americana*). This allowed the savanna to achieve 30% of the woodland's transpiration with only 11% of its sapwood area.

The implication for the land manager is that tree cover must be reduced substantially in order to generate meaningful gains in water yield. How substantially is not precisely known and will vary by ecoregion. However, Wu et al. (2001) suggest that on the western Edwards Plateau, watershed-level canopy cover must be reduced below 20% to generate substantial water yield gains. Conversely, it is clear that tree cover does not need to be brought to near-zero. Some canopy can remain at low density or potentially at higher density if it is distributed heterogeneously or located in areas where topoedaphic conditions limit water yield.

Location, intensity, and scale of treatment

The “distance to delivery,” (i.e. how far water must travel from the point of generation to the point of use) is an important factor in issues of scale. Effects may be dramatic at the small plot level but may be minimal or insignificant at the river basin level (Wilcox et al. 2006b). Hamilton (2008) points out that as “…the distance down the watershed and river basin becomes greater, other factors override or dwarf the effects experienced close to the treated area.” Some of these factors may be evaporation from stream channels, transpiration by riparian vegetation, loss to deep drainage, and activities in the basins of other tributary streams. Therefore, projects must be located as near as possible to the point of use.

The distance at which additional runoff becomes insignificant to water supply is likely variable in response to many factors, but the notion nonetheless should aid in the prioritization of treatments. However, in karst recharge zones where runoff is minimal and recharge is rapid, we can often consider the distance to delivery for recharge to be essentially zero because the point of generation (treated area) is directly over the point of use (aquifer).

Another factor affecting the efficacy of treatments is the intensity of treatment, or the degree of change within the treatment area. With respect to the Edwards Plateau, brush cover may need to be brought below 20-30% before significant water yield gains can be generated (Thurow 1998, Thurow and Hester 1997, Wu et al. 2001).

Lastly, brush management projects must be scaled appropriately to produce desired down-basin results. This means that on many brush-invaded sites with high canopy cover, much if not all of a catchment must be treated before measureable gains can be generated. For small catchments, such as internal drainage basins on karst geology, this may require treating and maintaining tens or hundreds of acres, but for large watersheds or river basins, this may mean thousands or even millions of acres. In other words, if, for example, results are desired at the river basin level, then treatments must be implemented at the river basin level.

These types of location, intensity, and scale issues may be why the brush control efforts in the non-karst North Concho River basin have so far failed to deliver substantial additional water yield to the main point of use (O.C. Fischer Lake near San Angelo, TX). Streamflow in the North Concho River in the Rolling Plains ecoregion of Texas declined significantly during the 20th century, presumably in response to brush encroachment, and brush control was proposed as a method for restoring higher flows. In this area, the predominant brush species in uplands is mesquite (*Prosopis glandulosa*), the removal of which has been shown to generate reductions in ET equivalent to about 4% of annual rainfall (Saleh et al. 2009). From 2001-2004, about 1,200 km^2 (300,000 ac) was cleared, but to date the most substantial increases in water yield have occurred only in the upper watershed with little additional water delivered to O.C. Fisher Lake (UCRA and TIAER 2006). In light of our literature analysis, one potential explanation for the underperformance of the project is that 1,200 km^2 represents only about 37% of the river basin. Another contributing factor is that water yield generated in the upper tributaries must travel over 112 km (70 mi) to the point of use.

Drought Influence

On any site, the relationship between vegetation and water yield is likely to change with respect to the availability of water in the system during wet or dry periods or as systems shift seasonally from being energy-limited to water-limited. Researchers in non-karst landscapes have found that the proportional effect of vegetation on water yield (percent change in water yield) is exaggerated during dry periods or in drier areas (Brown et al. 2005, Davie and Fahey 2005, Farley et al. 2005, Hamilton 2008, Scott et al. 2000, Trimble et al. 1987, Xiao et al. 1998) and we expect this general pattern to hold for karst areas as well. However, in very dry years, high ET - as seen in semi-arid pinyon-juniper woodlands ((Ffolliott and Stropki 2008)) - may negate the ET difference between treated and untreated areas.

One key concept in understanding these seasonal or climatic shifts is the water balance partitioning of large and small storms. Proportionally more of small rain events is intercepted by woody canopies than large events (Bazan et al. 2013, Owens et al. 2006). In addition, dry canopies intercept a greater proportion of rain events than wet canopies (Bazan et al. 2013). Thus, vegetation type may proportionally influence water yield to a greater extent during times of drought when rain events are often smaller and occur more infrequently. This will be important for water planning policy in many areas as preventing water shortages during drought is often equally or more important than increasing average water supply.

Recharge-runoff decoupling

Over karst geology, we often observe increased recharge (Banta and Slattery 2011, Dugas et al. 1998, Huang et al. 2006, Thurow and Hester 1997) but fail to observe significant changes in runoff (Banta and Slattery 2011, Bazan et al. 2013, Dugas et al. 1998, Thurow and Hester 1997, Wilcox et al. 2005) in response to reduced canopy cover. Runoff may tend to remain unchanged after brush removal because the infiltration rate of the previously-wooded soil remains high after canopy removal (Thurow and Taylor 1995).

Researchers may also simply fail to detect changes in runoff because of the relative rarity of runoff events on karst landscapes (Dugas et al. 1998). Dugas et al. (1998), Wilcox et al. (2006a), and Banta and Slattery (2011) all measured runoff to be less than 5% of annual precipitation at their research sites and failed to detect post-treatment changes in runoff. In contrast, Bazan et al. (2013) and Huang et al. (2006), who measured runoff to be 10% and as high as 34% of the annual water budget of their sites, respectively, each detected increases in post-treatment runoff. Thus, researchers may be more likely to encounter Type 2 errors pertaining to runoff than to recharge, particularly in areas where runoff comprises a small portion of the water budget.

This partitioning of the hydrologic response is important for agencies seeking to manage public expectations of brush control projects. Especially in karst areas, although water yield may be increased via recharge, it may not necessarily be visible to the pubic via runoff or streamflow. This may prompt citizens to ask, “Where is the water?” Conversely, increased runoff at small scales may be perceived as lost recharge. For this reason, it may be important to convey the message that in karst areas, additional runoff may become recharge by encountering recharge features in uplands or in streambeds.

The Need to Manage

A critical consideration for policy is that water yield gains can be lost without continued management. Without management, central Texas savanna can convert to woodland in as little as 30 to 40 years (Fowler and Simmons 2009). Further, Moore and Owens (2006) demonstrated that juvenile Ashe juniper released from competition following mechanical removal of larger trees exhibit much higher transpiration rates than other juvenile junipers not released from competition. The density of these small Ashe juniper (1ft to 5ft in height) released from competition have been observed to increase 2- to 8-fold in less than five years (WQPL 2016).

Implications are that water yield gained via brush control must be maintained by active management. Techniques such as prescribed fire that effectively remove all juveniles after mechanical removal of larger trees will more likely result in significant water yield gains and allow for longer treatment return intervals.

Conclusions

We believe that our findings have strong implications for water planning and land management. First and foremost, it is clear that except in special circumstances, water yield across the globe, including in karst systems, is negatively related to woody cover. It is also apparent that this relationship is non-linear, meaning that canopy cover must be reduced substantially in order to generate meaningful increases in water yield. Brush removal treatments must be located and scaled appropriately in order to produce significant down-basin results. However, over karst recharge zones, the down-basin distance can be effectively zero. There is also evidence from non-karst systems that the effects of woody cover on water yield may become more pronounced during dry periods. Last, water yield gains must be maintained through continued and holistic management of grassland systems.

At this point, we believe the most productive role for researchers is to a) increase the temporal and spatial scale of brush control field research to improve the accuracy of hydrologic models at large scales, perhaps by correlating historic changes in basin-level water yield to GIS-verified canopy cover and land use change, and b) work with practitioners to integrate research into grassland restoration projects.

For policy, we recommend that public brush management programs be implemented in areas where feasibility studies show treatment is likely to be most effective. The intensity and scale of treatment must be sufficient to generate meaningful additional water yield. Water planners should be realistic about the expectations for increased water yield when implementing brush control projects at large scales and be prepared to demonstrate changes in both streamflow and groundwater recharge. Water planners should also recognize that although the science may indicate that brush control for increased water yield is possible, the economic costs or social and political impediments to implementing treatments at a scale large enough to produce meaningful results and of maintaining low brush cover long-term may make such programs unworkable. In other words, although science might say it’s possible, reality may suggest otherwise.

Lastly, there is a valid concern among scientists and the public that wonton removal of brush for water yield without regard for negative impact to other ecosystem functions could cause unintended negative consequences such as erosion, degraded water quality, loss of wildlife habitat, and reduced rangeland productivity. Part of the intent of brush control programs should be long-term ecological restoration even if pursuing this goal reduces short-term water yield gains. Therefore, brush removal should be conducted within the context of broad, holistic land management plans that seek to improve many ecosystem functions and services along with water yield.

Table 1 . Regional experimental data from instrumented paired watersheds. Notes column lists variables other than reported canopy treatment that may have affected water yield results.

Source	Treatment	Effect	Notes
Dugas et al 1998	All Ashe juniper taller than 0.5m cut on 15 ha treatment plot. ET compared with adjacent control plot and pretreatment data.	Decrease in ET by 109, 120, and 29 mm during first, second, and third years.	Total canopy cover (all species) not reported.
Wilcox et al 2005	70% canopy removal and 100% canopy removal. Runoff compared to control watershed.	15-30 mm difference in runoff between 100% removal and control.	Treatment period includes 4 years post treatment, including recovery from severe drought and exceeding anticipated water yield benefit interval observed by Dugas 1998. Recharge and ET not measured.
Huang et al 2006	60% of the catchment was cleared of Ashe juniper.	Streamflow increased by 46mm annually.	Weak treatment intensity (canopy reduced from 90% cover to 45% cover) compared to minimum for anticipated water yield benefit . Subsurface drainage conditions unknown (recharge within the surface catchment may emerge elsewhere, and springflow may have originated from beyond the surface catchment). Recharge and ET not measured.
Banta et al 2011	Approx.. 70% of Ashe juniper cut and left in place.	Decrease in ET equiv. of 8% annual rainfall. Recharge increase by 84 mm annually. Runoff unchanged.	Weak treatment intensity compared to minimum for anticipated water yield benefit. Total canopy treatment effects (all species) unreported.
Bazan et al 2013	100% of Ashe Juniper removed, leaving canopy cover around 30%.	Runoff increased equiv. of 7% of annual rainfall. Conduit flow unchanged.	Weak treatment intensity compared to minimum for anticipated water yield benefit . Diffuse (slow) recharge (Hauwert 2014), lateral subsurface flow, and ET not measured.

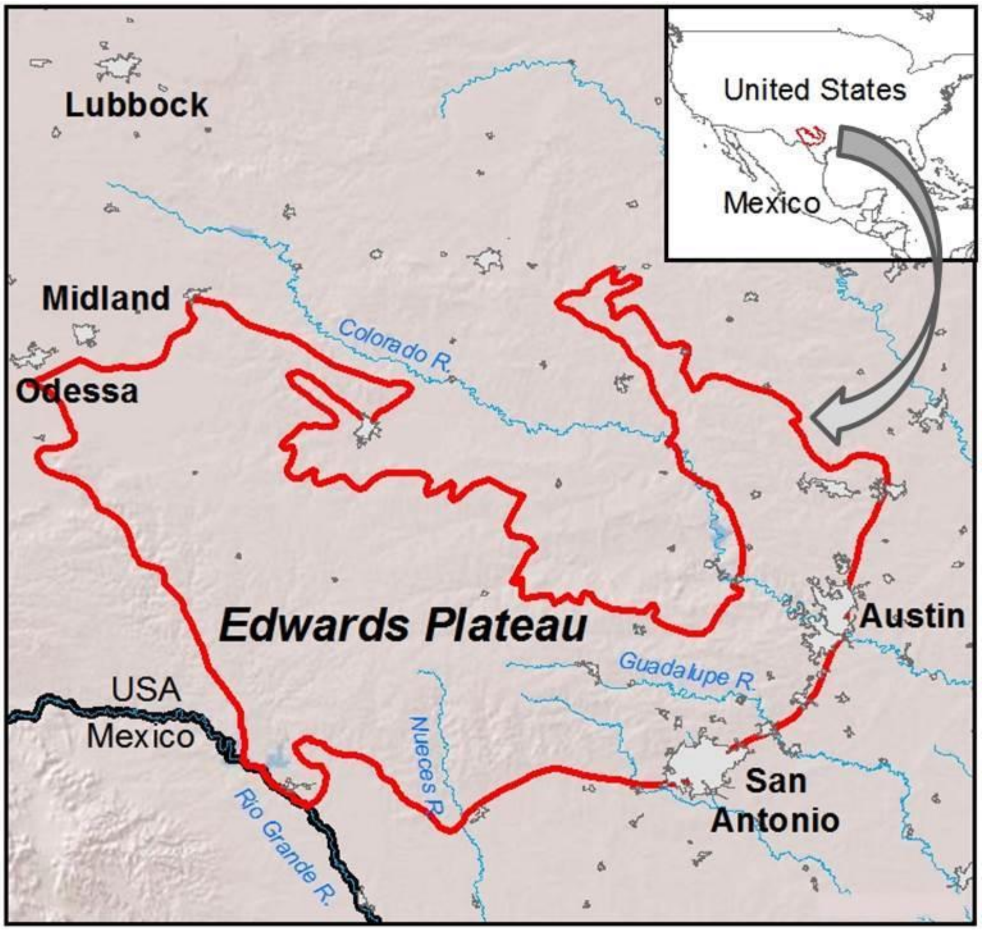

Figure 1. Edwards Plateau, outlined in red. Urban centers in grey.

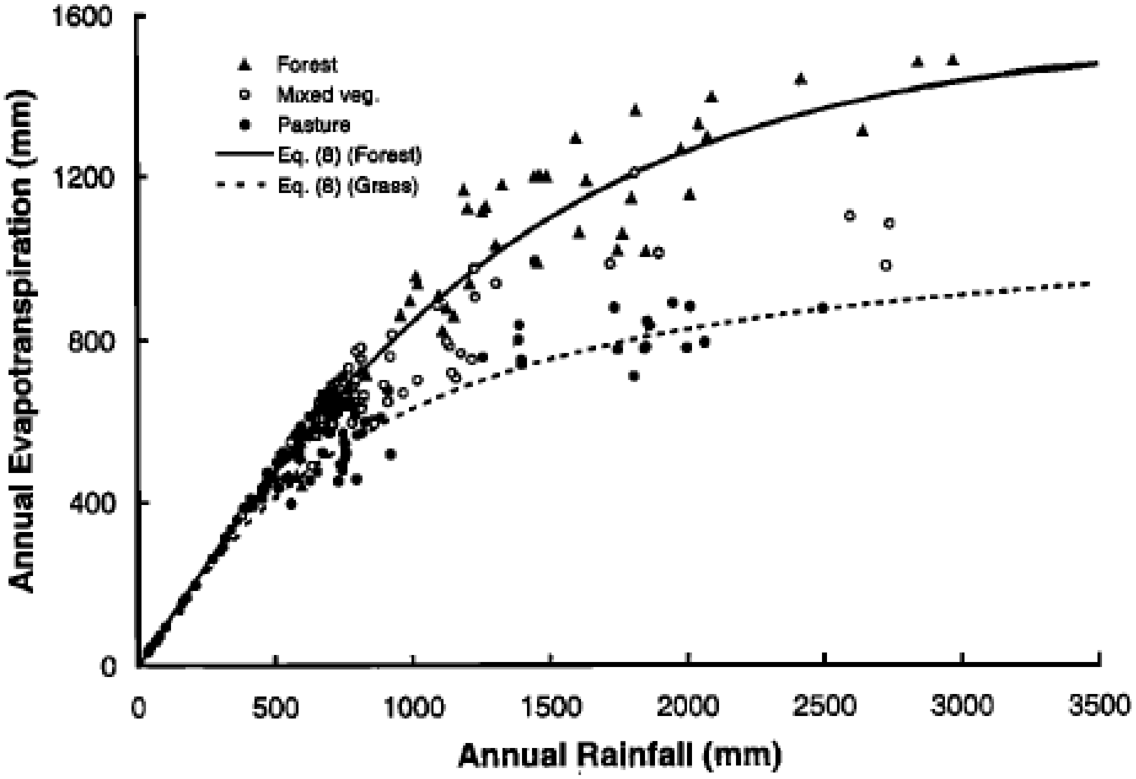

Figure 2. Relationship between annual evapotranspiration and rainfall for forest, mixed vegetation, and pasture. Figure taken from Zhang et al. (2001).

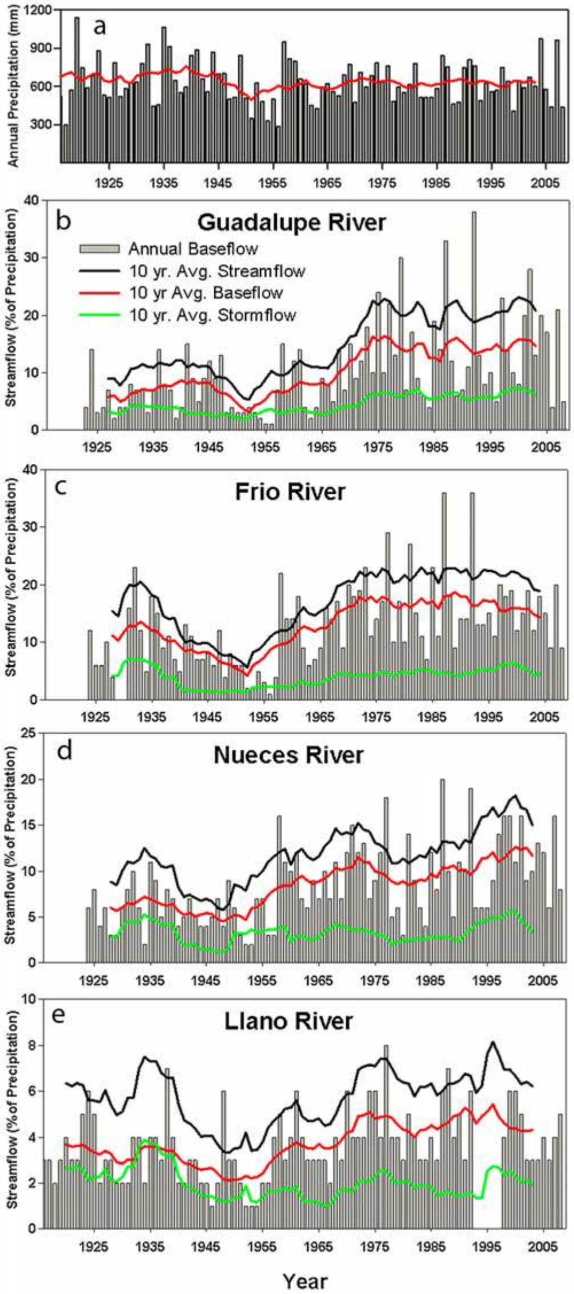

Figure 3. (a) Composite annual precipitation for the Edwards Plateau. The columns represent annual precipitation. The solid line is the 10-year moving average. (b–e) Components of streamflow for the Guadalupe, Frio, Nueces, and Llano rivers. Figure taken from Wilcox and Huang (2010).

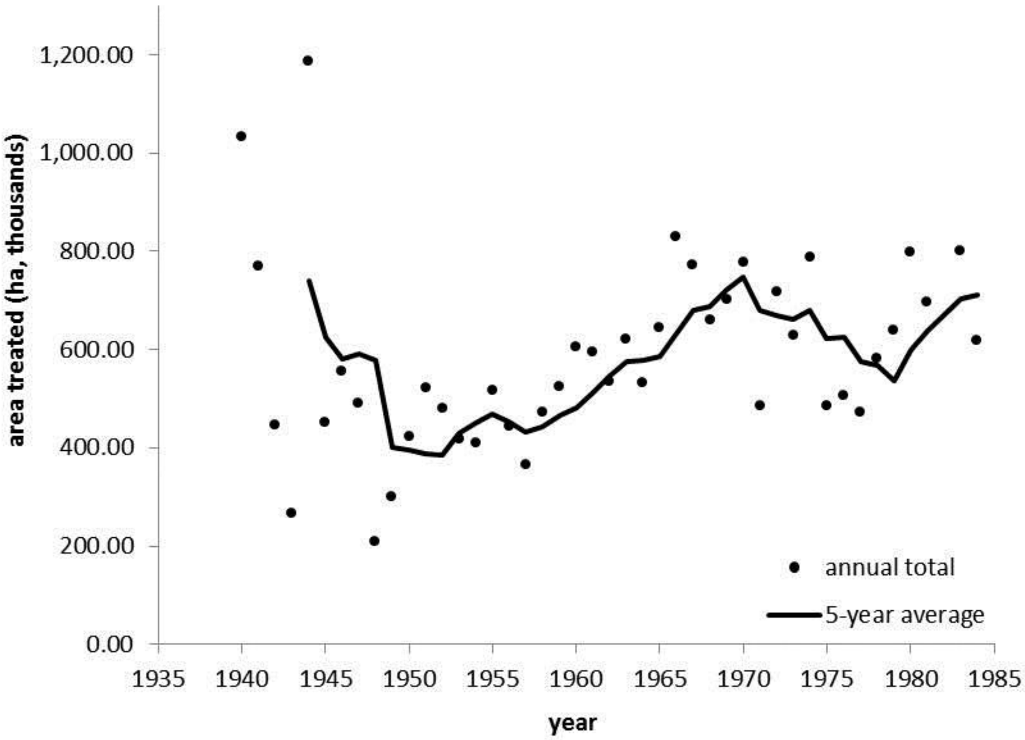

Figure 4. Annual totals and five-year moving average of hectares of brush control conducted in Texas from 1940 to 1984. Data taken from TSSWCB (1987).

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