TEXAS A&M AgriLIFE
Teaching • Research • Extension • Service

Agriculture is Life!

TR-338
2008

Effects of Brush Management on Water Resources

By:

C. Allan Jones and Lucas Gregory, Texas Water Resources Institute, Texas A&M AgriLife

Texas Water Resources Institute Technical Report
November 2008

Texas Water
Resources Institute
make every drop count

TEXAS A&M AgriLIFE
Teaching • Research • Extension • Service

TR-338
2008

Effects of Brush Management on Water Resources

By
Allan Jones and Lucas Gregory
Texas Water Resources Institute
Texas A&M AgriLife

November 2008

Texas Water
Resources Institute
make every drop count

Summary

For several decades, land managers have cleared brush species, such as mesquite and juniper (cedar), and observed increases in spring and streamflows. Scientists have also conducted numerous studies in which they have measured the effects of brush removal on different aspects of rangeland hydrology. These include the amount of rainfall that is intercepted and held by the plant leaves, surface runoff, spring flow, water use by individual plants and plant communities, fluctuation of shallow water tables, and streamflows. Considering this very diverse information, many scientists agree on several points:

1. The roots of some brush species extract water from greater depths than do grasses and forbs, and brush control can reduce the total amount of water used by vegetation.
2. Brush and other deep-rooted vegetation growing over shallow aquifers near streams can be expected to use large amounts of groundwater, likely reducing the amount in both the interconnected stream and aquifer.
3. Removal of brush like juniper and live oak from upland areas some distance from streams may increase streamflow and/or recharge aquifers especially when:
    a. The brush canopy is dense and intercepts substantial amounts of rainfall (for example: dense juniper [cedar] or live oak stands), effectively reducing the amount of rainfall reaching the soil surface, and
    b. Soils, subsoils and/or geologic strata are permeable, and streams in the area are fed by seeps and springs. Water can quickly percolate below the roots of grasses and forbs and move through subsurface pathways to local streams or aquifers.
4. Brush control in upland areas is unlikely to increase significantly water yields if soils and geologic formations are not conducive to increased runoff and/or subsurface flows to streams or to aquifers.
5. For brush control to have substantial long-term impacts on water yield, most or all of the woody vegetation in the treated area should be killed, and regrowth of brush

and herbaceous vegetation should be controlled so that it is less dense and more shallow rooted than the pretreatment vegetation.

6. New science-based tools can help pinpoint locations where brush control should substantially increase water flows in streams.
7. A geographically targeted brush control program with careful scientific verification of impacts is needed to guide long-term brush control policies.

Introduction

For many years, brush management has been an important tool in maintaining livestock and wildlife production on rangelands. It has long been recognized that water used by brush is not available to the grasses and forbs, and clearing brush typically stimulates grass and forb growth.

Historically, many brush species have served as a vital part of rangeland habitats in Texas and the southwestern United States. The range and coverage of woody plant species has increased in recent times. Van Auken (2000) describes this conversion of grasslands or native rangelands and savannas to woodlands as woody plant encroachment. He attributes much of the increased density of woody plants to a combination of changing climates, overgrazing, and fire suppression. Overgrazing and fire suppression can easily be linked to the expansion of western settlement (Blackburn, 1983; Archer, 1994; Dugas et al. 1998) and have served as the primary catalyst in the increases in upland woody species, such as Ashe juniper and mesquite. Other species have been introduced to the state and have adapted quite well. Salt cedar was introduced to the United States in the early 1800s as an ornamental and in the early 1900s, it was used as a means for streambank stabilization (Everitt, 1998). Since then, salt cedar has taken over large areas of riparian habitats in the western United States. It has drastically altered the vegetative composition of these plant communities and the hydrology of these areas (Hart et al., 2005). Ultimately, brush has and always will play a vital role in Texas landscapes, but human influences have greatly altered the balance between brush and herbaceous plant communities and rangeland hydrology. This realization took hold in the early 1960s and brush clearing efforts began shortly thereafter in an attempt to correct these ecologic and hydrologic modifications.

In the 1960s, the USDA Soil Conservation Service (SCS) cleared brush, primarily mesquite, from the Rocky Creek watershed near San Angelo and the creek began flowing again for the first time in many years. This was sufficient evidence for SCS and the ranchers. They then began clearing brush, not only to increase forage for their livestock, but also to restore water in West Texas streams (Kelton, 1975).

Over the years following the work in the Rocky Creek watershed, many more scientific studies have demonstrated the impacts that brush has on the various components of rangeland hydrology, including the amount of rainfall intercepted by different species of brush, transpiration of water from plants and from plant communities (evapotranspiration), runoff from the soil surface, infiltration into the soil, and subsurface movement of water to streams via seeps and springs. From this research, scientists have concluded that under certain conditions brush control can substantially increase the amount of water reaching streams and aquifers. Under other conditions, brush control can have little or no effect (Bosch and Hewlett, 1982; Hibbert, 1983; Huxman et al., 2005; Rainwater et al., 2008; Thurow, 1990; Thurow et al., 2000; Wilcox, 2002; Wilcox et al., 2006b). For example, Wilcox et al. (2006b) reviewed available literature and concluded that brush control is most likely to increase water yield in three key areas: 1) riparian areas with accessible groundwater and dominated by invasive riparian species such as salt cedar, 2) upland landscapes with woody species such as juniper and oak on soils that allow rapid deep drainage such as shallow or highly permeable soils over fragmented karst limestones like those in the Edwards Plateau and 3) mesquite growing on deep sandy soils like those in the Carrizo-Wilcox Aquifer recharge zone. They also concluded that areas where brush control is least likely to increase water yields significantly are those with deep soils, deep or absent groundwater, and where no subsurface flow to springs occurs.

Sterling Creek in the North Concho River watershed, once dried, is a perennial-flowing creek after brush control (May 2005).

The purpose of this white paper is to present the scientific literature on this important issue in a form that will be useful to decision makers considering public policies that encourage brush control in Texas for water yield enhancement. For this paper, a working definition of “brush” is “unwanted woody vegetation on range lands, including but not limited to juniper (cedar), mesquite, salt cedar, and oak.”

Because the benefits of well-designed brush control programs on rangeland productivity, livestock production, and rural economic activity are widely understood, the focus here will be only on the effects of this conservation practice on the amount of water in our streams and aquifers. To facilitate communication and comparisons among studies, in most cases water savings resulting from brush control are expressed in English rather than metric units, and spring flows, streamflows, aquifer recharge, etc. have been converted to units of inches or feet. For example, if brush control is reported in a particular experiment to have increased streamflow by 2.0 inches per year, it means that the annual streamflow increased by an amount equivalent to 2.0 acre-inches per acre of the watershed (usually per acre of the watershed treated). One acre-inch is equal to 27,154 gallons, and one acre-foot equals 325,851 gallons.

What Do We Know?

In the following sections, we attempt to describe clearly the current state of scientific knowledge about the effects of brush control on rangelands, with emphasis on Texas and the southwestern United States.

The roots of some brush species extract water from greater depths than do grasses and forbs, and brush control can reduce the total amount of water used by vegetation.

Ranchers have long observed that, during dry periods, woody species such as mesquite, juniper, and live oak stay green after most grasses and forbs mature and turn brown. In addition, the roots of brush species are often observed far deeper in the soil (as seen in road cuts and deep gullies) than grass roots. Based on these observations, it has been widely assumed that brush can use water from deeper in the soil than can grasses and forbs.

This assumption was confirmed in work conducted by Jackson et al. (1999) that found roots of woody plants in 14 of the 19 caves they studied in the Edwards Plateau region. By analyzing root DNA, they determined that the roots of six species penetrated at least 17 feet. Roots of Ashe juniper and live oak were found as deep as 27 feet and 73 feet, respectively.

Richardson et al. (1979) studied runoff and calculated evapotranspiration from soil moisture in two mesquite-infested watersheds on deep clay soils of the Blackland Prairie near Riesel. The watersheds were monitored for two years prior to chemical control of the mesquite and for three years after treatment. In this experiment, mesquite control reduced evapotranspiration by 3.1 inches per year. This reduction was the result of decreased use of soil water between 1 and 5 feet below the surface, especially late in the growing season. These results, like those of Jackson et al. (1999), suggest that brush species often use water from deeper in the soil than grasses and forbs.

Scott et al. (2000) measured ET from two plant communities, a perennial grassland and a mesquite-dominated shrubland, on a river floodplain in Arizona. They found that the mesquite shrubland extracted water from deeper in the soil profile than the grassland. Over the course of a year, the grassland used approximately 10.8 inches of soil water, and the mesquite shrubland used approximately 14.8 inches. But there was little indication that the shrubland used a significant amount of water from the shallow aquifer, which was over 30 feet deep at the site.

Saleh et al. (2008) measured evapotranspiration on two 200-acre watersheds within the North Concho watershed near San Angelo. Brush, primarily mesquite, was removed from one of the watersheds and left undisturbed on the other. The watershed on which all mesquite had been removed averaged 11 percent less evapotranspiration over two growing seasons (May-October). The difference was slightly greater (14 percent) during the warmer June-September period, and the difference was greater in a dry June-September period (4.8 inches, 17 percent) than a wetter period (11.8 inches, 12 percent). These results, while still awaiting publication, are consistent with those of Richardson et al. (1979), Dugas and Mayeux (1991), and Scott et al. (2000), who concluded that mesquite removal decreased evapotranspiration in the Blackland Prairie, Rolling Plains, and Arizona, respectively. In these studies, mesquite roots were presumably able to reach and extract water below the rooting depth of grasses and forbs.

Of course, if brush is allowed to re-infest the treated area or other deep-rooted replacement vegetation is allowed to grow so that its leaf area is comparable to the brush prior to treatment, potential water savings from brush control will likely be negated.

Brush and other deep-rooted vegetation growing over shallow aquifers near streams can be expected to use large amounts of ground water, likely reducing the amount in both the interconnected stream and aquifer.

Streams often change course over geologic time, depositing layers of sands and gravels in intricate patterns. The water in these deposits can remain in hydrologic contact with the water in the stream, creating shallow "riparian aquifers." Water can enter these shallow riparian aquifers in four ways: from flooding of the bottomlands along the stream, from rainfall that percolates downward from soils directly over the aquifer, by subsurface flow from nearby uplands, or by flow directly from the stream when the water level in the stream is higher than that in the aquifer. When the water level in the aquifer is higher than the water in the stream, water returns from the aquifer through springs to the stream. Woody vegetation growing near streams can often use large amounts of water from riparian aquifers. This situation has been clearly demonstrated in New Mexico, where Cleverly et al. (2002) reported that a salt cedar-dominated site that flooded twice a year used 48 inches of water over a 157-day growing season while one that did not flood used 29 inches. This is well within the range of daily salt cedar water use in studies reviewed by Cleverly et al. (2002). Several of these studies measured maximum water use by salt cedar stands in hot and dry areas of over 0.37 inches per day. Nagler et al. (2008) obtained similar results along the Lower Colorado River in the Cibola National Wildlife Refuge. There, salt cedar growing on river terraces where the water table was 10 to 13 feet deep used from 43 to 55 inches of water per year; however, this water use equates to only 1 to 2 percent of annual river flow (McGinly 2008, Nagler et.al,2008).


Salt cedar being sprayed on the Pecos River

Owens and Moore (2007) found similar water use by a young and dense salt cedar stand near the Rio Grande. They used sap flow measurements to estimate a maximum salt cedar transpiration rate of 0.23 inches per day and a total of 41.4 inches over a 180-day growing season. A mature, less dense stand very close to the Pecos River used much less water, a maximum of only 0.01 inches per day, possibly because the trees were growing in very salty soils (G. W. Moore, personal communication).

Hart et al. (2005) measured the daily rise and fall of the shallow riparian aquifer along the Pecos River in Texas before and after and with and without herbicidal control of salt cedar. The daily variation in the water table under salt cedar stands clearly demonstrated that during the daylight hours the plants were using substantial water from the shallow aquifer associated with the stream. At night when plant water use decreased, the water table level recovered. The study demonstrated that water use ceased when the salt cedar was killed with herbicide. Over a three-year period, annual water use at the untreated site varied from 68 inches to 80 inches. For the site where salt cedar was killed, the annual water use was 116 inches the year prior to treatment and declined to only 7 inches the year after.

Although salt cedar is the most well known example of unwelcome riparian vegetation that uses water from Texas streams, mesquite, juniper, giant cane, and other species often invade abandoned croplands and overgrazed rangelands near streams. For example, Unland et al. (1998) measured water use by several vegetation types in a riparian corridor between one-half and one mile wide along the Santa Cruz River in southern Arizona. During a one-year period with a total of 28.1 inches of rainfall, the vegetation, consisting of willow-dominated and mesquite-dominated plant communities (about 2 acres of mesquite for each acre of willow), used a total of 44.7 inches of water. Much of this water use was without doubt from the shallow aquifer associated with the river. Similarly, work conducted by Nagler et al. (2008) found that salt cedar growth in the Cibola National Wildlife Refuge near the Lower Colorado River used an annual average of 43.2 inches of water in an environment where the annual average rainfall is only 3.1 inches. In contrast, short low-density vegetation growing on abandoned agricultural fields nearby used only 6.2 inches of water.

Tromble (1972) also measured the daily rise and fall of a shallow riparian aquifer with a typical depth of 10 to 13 feet below a mesquite woodland in southeastern Arizona. From these data, he estimated water use by the vegetation of up to 0.42 inches per day. Similar values of mesquite and salt cedar evapotranspiration from shallow aquifers have been reported by Gatewood et al. (1950) and Qashu and Evans (1967).

Moore et al. (2008) found significant amounts of salt cedar transpiration (up to 36 percent of total daily transpiration) at night. This nocturnal water use would tend to reduce diurnal variation in water table levels and cause underestimation of total water use; essentially, aquifer levels do not rise as much as they would if no transpiration occurred at night. This suggests that other studies of salt cedar water use that measured diurnal variation in the shallow water table may have underestimated total water use.

Giant Cane along the Arroyo Colorado in the Lower Rio Grande Valley

Scott et al. (2003) measured water use by both mesquite trees and the grasses and forbs growing in a mesquite woodland within about 500 yards of the Upper San Pedro River in southeastern Arizona. In this location, the mesquite tree roots were observed approximately 33 feet below the soil surface, the approximate depth of the water table. Evapotranspiration measurements of the mesquite canopy and understory plants, as well as measurements of daily fluctuations of the water table, led the authors to conclude that the mesquite trees obtained most of their water from a deep groundwater source, whereas the understory vegetation primarily used recent precipitation stored near the soil surface. In various periods from June through September, water use by the mesquite alone ranged from about 0.04 to 0.12 inches per day.

Giant cane is another exotic invasive species that has colonized many riparian areas across Texas. Though few direct measurements of water use by giant cane have been made in Texas, studies in California found between 3.8 and 4.4 feet of water use per year. These values are within the range of water use measured in salt cedar (Bell, 1997; Jackson et al., 2002). With 60,000 acres of giant cane in the riparian areas of the Rio Grande alone, replacement of this species with vegetation that uses less water could increase available water significantly.

Several of the studies and reviews cited above suggest that salt cedar, mesquite, giant cane, and other woody species growing near streams over associated shallow aquifers can use up to 4 acre-feet of water for each acre of vegetation. Much of this water can be saved or “salvaged” by killing the woody vegetation and replacing it with low-density, shallow-rooted grasses and forbs. These water savings may be reduced or lost if the original vegetation or other woody species like willows are allowed to grow again on the area previously treated (W. Hatler and C. Hart, personal communication). However, even if the long-term effect of salt cedar control is to save only 1 acre-foot of water for each acre treated, the impacts on water flow can be significant. For example, if clearing 13,500 acres of salt cedar on the Pecos River from 1999 through 2005 saves only 13,500 acre-feet of water per year, the increased flow of the river and/or storage in the riparian aquifer is equivalent to 59 percent of the average flow of the river at Girvin (23,000 acre-feet per year) (Hart, 2005; Miyamoto et al., 2005).

Removal of brush like juniper and live oak from upland areas may increase streamflow and/or recharge aquifers, especially when:

a. ***The brush canopy is dense and intercepts substantial amounts of rainfall (for***

example, dense juniper [cedar] or live oak stands), effectively reducing the amount of rainfall reaching the soil surface, and

b. ***Soils, subsoils and/or geologic strata are permeable, and streams in the area are fed by seeps and springs. Water can quickly percolate below the roots of grasses and forbs, and subsurface pathways can conduct water from the uplands to local streams or aquifers.***

Water that is intercepted by and remains in the leaf canopy after a rain event evaporates without ever reaching the soil surface. Water that passes through the leaf canopy and reaches the ground either runs off or percolates into the soil. Once in the soil, the water can be stored in the root zone until it evaporates from the soil surface, it is transpired by the vegetation, or it percolates below the root zone, where it either recharges an aquifer or reaches nearby streams via seeps and springs.

Of course, rainfall intercepted by the leaf canopy has little or no effect when rainfall is not enough to produce runoff or deep percolation below the root zone. However, when rainfall is sufficient, additional water that reaches the soil surface when no brush is present can substantially increase runoff and/or deep percolation. For example, Thurow et al. (1987) estimated that near Sonora live oak mottes intercepted 46 percent of the annual precipitation, compared with 18 percent interception by sideoats grama and 11 percent by curlymesquite grass.

Similarly, Thurow and Hester (1997) summarized studies on the Edwards Plateau near Sonora. They concluded that clearing brush (36 percent juniper and 24 percent oak) increased the amount of rainfall reaching the soil by 6.6 inches per year and increased deep drainage by 3.7 inches per year during a two-year period with 22.6 inches of annual rainfall. In these studies runoff was minimal (0.2 inches per year) due to high soil infiltration rates. This work was reviewed by Thurow et al. (2000) along with other works (Redecker et al. (1998), Carlson et al. (1990), Carlson and Thurow (1996)) and they concluded that water yield from grass rangelands on the Edwards Plateau near Sonora, Texas exceeds those of rangelands with brush cover of 15 percent or greater.

In Texas, controlling juniper (thereby reducing interception) can increase both surface runoff and spring flow. For example, Huang et al. (2006) measured spring flow and total flow at the base of a forty seven-acre watershed on the Edwards Plateau in Comal County for two years prior to juniper control and two years after control. Over the course of the four years, total streamflow (consisting of both storm flow and baseflow) varied from 4 percent of rainfall in the driest year to 34 percent in the wettest year, and averaged 22 percent of rainfall overall. Baseflow (spring and seep flows) contributed approximately half the total. On a per-rainfall event basis, average runoff was 0.22 inches before juniper removal and 0.35 inches afterward, suggesting that juniper removal resulted in a 1.8 inch (60 percent) annual increase in total streamflow.

These results are consistent with the results of two reports from the Seco Creek watershed in Medina County. Dugas et al. (1998) found that for the first two years after juniper was cleared, total evapotranspiration was about 4.3 inches per year less on the cleared site than on the uncleared site. This finding illustrates how reductions in interception and vegetative water use can alter the hydrology of a treated site. In the third year after brush clearing, Dugas et al. (1998) found that both sites produced approximately equal amounts of evapotranspiration, probably due to much greater growth of perennial grasses as well as compensatory growth of other woody plants on the cleared site. The authors suggest that the beneficial effects of juniper control might have continued if compensatory vegetation growth had been suppressed by grazing and follow-up brush control. Similarly, Wright (1996) reported increases in spring flow of approximately 1.6 inches per year as a result of juniper control in the watershed.

Grubber removing mesquite

A number of studies conducted outside Texas are consistent with those cited above. For example, Bosch and Hewlett (1982) reviewed ninety-four watershed experiments from around the world to determine the effects of vegetation changes on water yield. Virtually all the experiments found that reducing vegetation cover (and interception) increases water yield from watersheds. On average, for pine and eucalypt forests water yield increased by an annual average of 1.6 inches for each 10 percent reduction in canopy cover. For deciduous hardwood and "scrub" vegetation, the corresponding increases in water yield were 1.0 inches and 0.4 inches, respectively. Experiments in Arizona, California, and Utah were particularly relevant to the situation in western Texas. In eight experiments, vegetation (oak woodland, chaparral, or juniper-pinyon) was cleared in areas with average rainfall between approximately 18 inches and 27 inches. The average annual water yield increase over several years following clearing varied from "non-significant" to about 5.2 inches with larger increases in the experiments with greater rainfall. The average streamflow for these eight experiments increased by approximately 2.0 inches, more that doubling the mean annual streamflow of 1.8 inches for these sites prior to clearing the vegetation.

In view of the studies summarized above, it seems likely that clearing dense juniper and live oak brush in the Edwards Plateau or similar areas can produce 1 to 4 acre-inches of additional water per year for each acre of brush cleared. Of course, as discussed in the previous section, brush control must be maintained and excessive compensatory growth of herbaceous vegetation must be controlled by grazing or other means in order to sustain these increased water yields.

Brush control in upland areas is unlikely to significantly increase water yields if soils and geologic formations are not conducive to increased runoff and/or subsurface flows to streams or to aquifers.

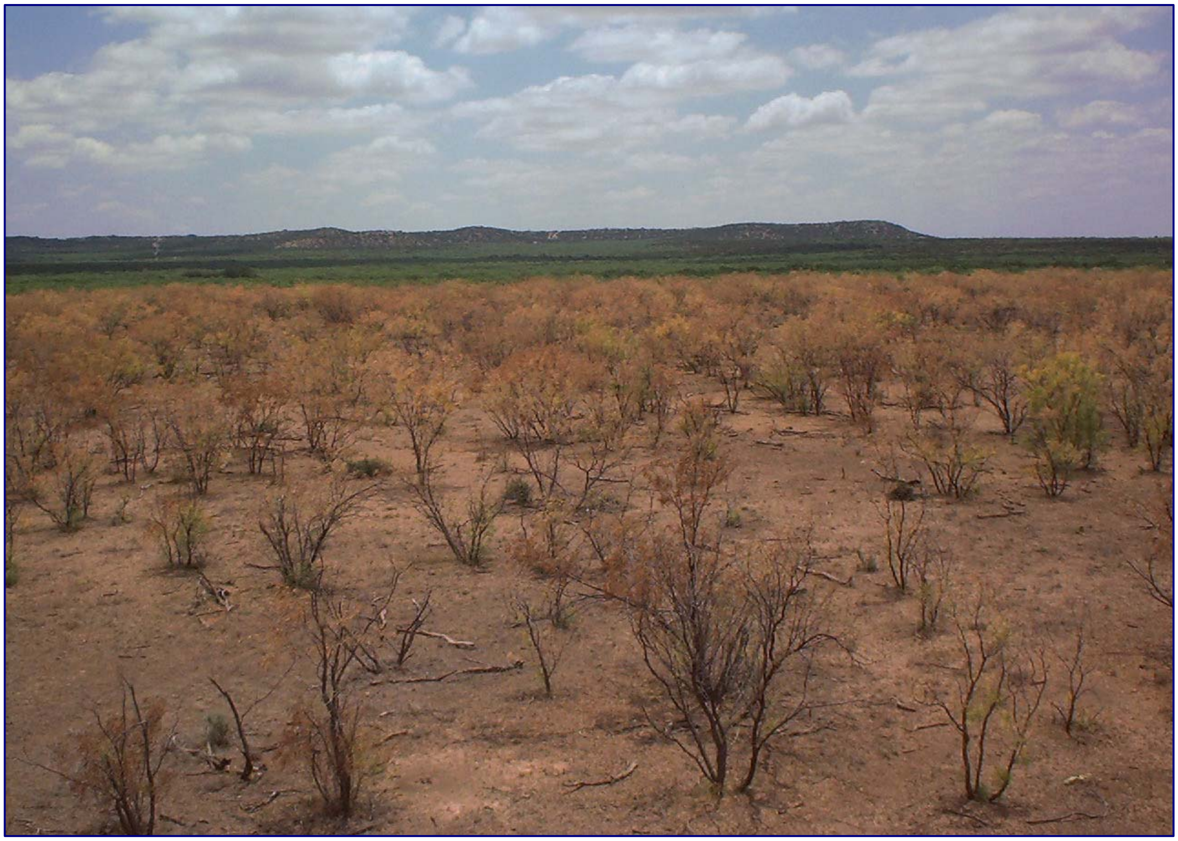
Brush control in upland areas receiving very little annual rainfall is unlikely to reliably increase water yields because runoff and/or subsurface flows are seldom large. Wilcox et al. (2006b), Ball and Taylor (2003), and Bosch and Hewett (1982) concluded that control of brush on areas receiving less than 18 inches of rainfall annually is not likely to increase water yields. Similarly, brush control on sites with deep permeable soils and no local springs or shallow aquifers is unlikely to generate significant increases in streamflows or aquifer recharge because these soils and geologic formations are not conducive to increased runoff and/or lateral subsurface flows to streams or to aquifers (Wilcox et al. 2006b).

For example, Carlson et al. (1990) measured evapotranspiration, deep drainage, soil storage, and runoff from lysimeters with and without mesquite on the Rolling Plains near Throckmorton. Over a three-year period, they found little effect of mesquite removal on deep drainage or surface runoff. This response seems to be the case in the Rolling Plains of North Texas where soils are permeable and deep, runoff rarely occurs, and mesquite dominates the woody vegetation. Though brush control in these cases may benefit the rancher by stimulating compensatory forage growth, it does not necessarily increase streamflows or aquifer recharge.

For brush control to have substantial long-term impacts on water yield, most or all of the woody vegetation in the treated area should be killed, and regrowth of brush and herbaceous vegetation should be controlled.

As mentioned above, any effort to control woody vegetation to increase water availability must also consider long-term maintenance of that control. For example, if only the juniper is removed from an oak-juniper woodland, the oaks and other species will often respond to fill in spaces formerly occupied by the juniper, reducing or even eliminating the benefits of the juniper control. The same effects may be seen if brush species are allowed to regrow or if grasses and forbs regrow to much greater biomass and leaf area than they had before the brush was controlled. Their greater leaf development can intercept more rainfall, slow runoff, and transpire more water to offset the otherwise beneficial hydrologic effects of brush control.

For example, Dugas and Mayeux (1991) found that chemical control of mesquite in mid-summer immediately decreased evapotranspiration by up to 40 percent, compared with the



Dead mesquite after brush control

untreated plot. However, the plots were not grazed, and during the subsequent summer, grass and forb growth increased dramatically in the treated plot, and evapotranspiration was only reduced by 7 percent compared with the control. Brush removal in this situation may simply allow more water to be stored in the soil for use by the remaining grasses and forbs. Similar effects were observed by Dugas et al. (1998) in their study of juniper control in the Seco Creek watershed on the Edwards Plateau (see discussion above).

Moore and Owens (2006) also emphasized the importance of completely clearing juniper within an area and maintaining control after initial clearing. Otherwise, juvenile trees remaining after larger trees are cleared will compensate with rapid growth and water use, significantly decreasing the positive impacts of brush clearing on forage production and water yield.

New science-based tools can help pinpoint locations where brush control should substantially increase water flows in streams.

Over the last decade, researchers have developed and used simulation models and decision tools to pinpoint locations where brush control is most likely to increase water yields to streams and/or aquifers.

Redecker et al. (1998) used SPUR (Simulation of Production and Utilization of Rangelands-91) model to simulate the effects of broad-scale brush control on the Cusenbary Draw watershed (80 square miles) on the Edwards Plateau. Based on surveys of ranchers in the watershed, they concluded that landowners would enroll 40 percent of their land in a brush control program, and the results would be a two-fold increase in water yield from the rangelands on which brush was controlled (from 0.80 to 1.60 inches per acre per year). This study did not identify target areas where brush control would yield the most water.

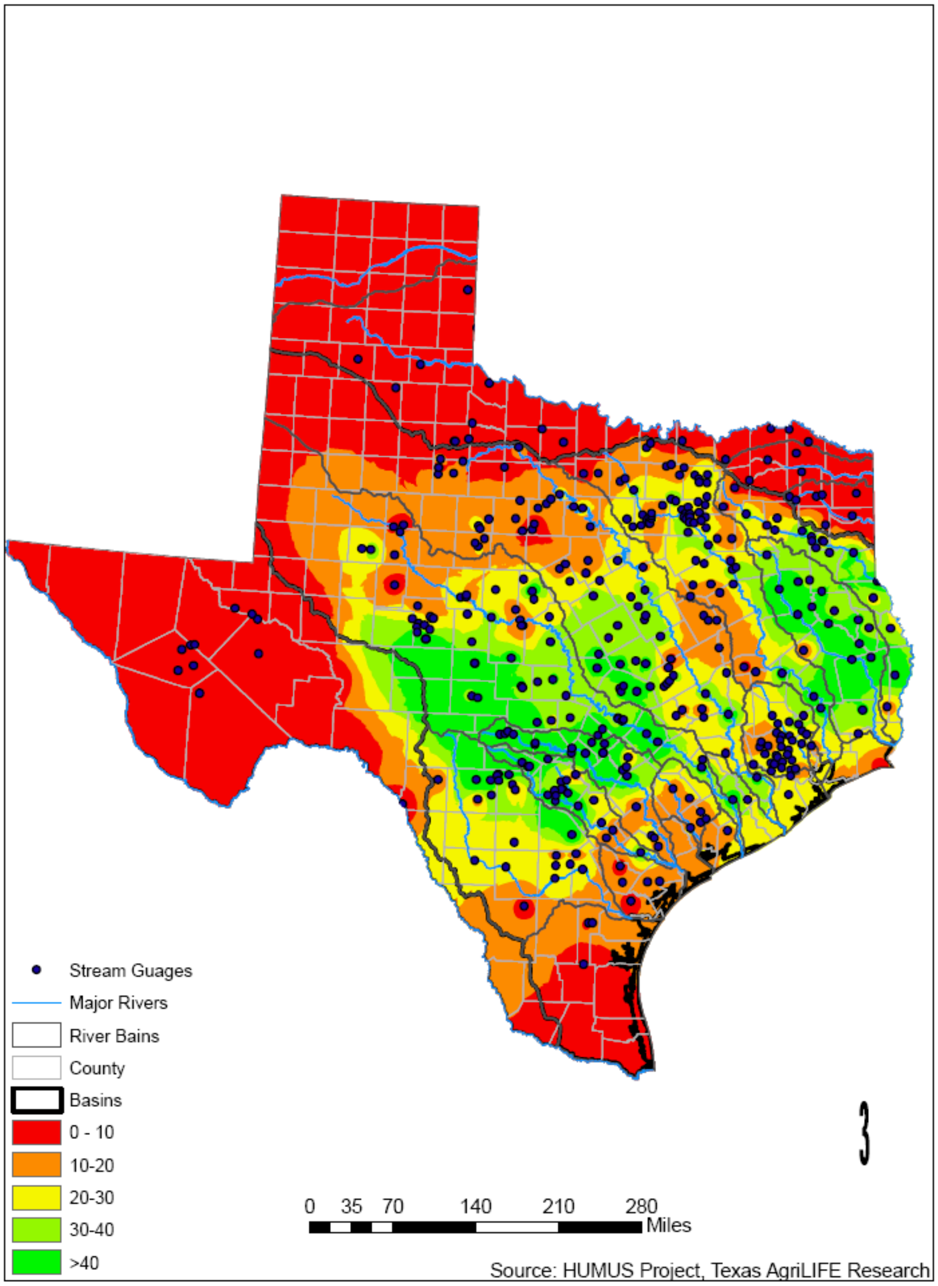
Arnold et al. (2008) used the SWAT (Soil and Water Assessment Tool) model to estimate the effects of brush control on streamflows for eight Texas river basins composed of numerous sub-basins. The studies were conducted to provide guidance for the brush control cost-share program conducted by the Texas State Soil and Water Conservation Board and are reported in detail in Texas Agricultural Experiment Station (2000). Results suggested that little increase in streamflow (baseflow plus surface runoff per unit treated area) can be expected where mean annual rainfall is less than about 18 inches, but substantial streamflow increases (2 and 4 inches per year) could be expected with mean annual rainfall of 24 and 30 inches, respectively.

Afinowicz et al. (2005) also used SWAT to estimate the effects of brush control on water yields in the Edwards Plateau. Considering the area where brush was removed over a ten-year period, this simulated removal of brush reduced evapotranspiration by an average of 1.8 inches per year, increased runoff and lateral flow to the stream by 0.4 inches per year, increased baseflow to streams by 0.1 inches per year, and increased deep aquifer recharge by 1.2 inches per year.

The hydrologic estimates of these modeling studies are generally consistent with experimental data reported by Bosch and Hewlett (1982), Huang et al. (2006), Dugas et al. (1998), Thurow and Taylor (1995), and Owens and Knight (1992).

The Spatial Sciences Laboratory at Texas A&M University has developed a completely independent method to identify areas of Texas with substantial baseflows, which are indicative of geology and soils that allow precipitation to percolate into shallow aquifers and return to nearby streams via springs (R. Srinivasan, personal communication). This method is based on long-term streamflow data from a large number of U. S. Geological Survey stream gaging stations (Figure 1). Daily streamflow data were analyzed mathematically to distinguish between overland and baseflow components for each gage. The ratios of baseflow to total streamflow for all points were interpolated to generate the map showing the fraction of total streamflow that is baseflow. In general terms, areas with the highest percentage of annual baseflow correspond quite well with major portions of the Edwards Plateau, the Cross Timbers and Prairies, and the East Texas Pineywoods. These are areas where rainfall is sufficient and soils and geology are permeable enough for precipitation to penetrate the soil and move laterally to nearby streams. The green, and perhaps yellow, areas appear to offer the greatest opportunity for upland brush control to produce significant increases in water yield.

Another approach uses rules based on consensus expert opinion to target hydrologically sensitive areas within a watershed (R. Srinivasan, personal communication). An expert system based on a currently available, multi-layered geographic information system has been developed to identify areas within a watershed with the greatest potential for increasing water yield through vegetation management (increased streamflow and/or groundwater recharge). The tool incorporates rules related to: 1) the presence or absence of brush, 2) topography of the watershed, 3) proximity of the brush to a stream or drainage path and 4) the likelihood of precipitation becoming aquifer recharge.



Source: HUMUS Project, Texas AgriLIFE Research

Figure 1. Annual average baseflow as a percentage of total baseflow.

Rainwater et al. (2008) developed a similar approach to select the most appropriate sites for brush control to increase water yields. Evaluation of watersheds should consider: 1) characteristics of the watershed (soils, slope, land use, vegetation and brush distributions, and proximity of brush the stream), 2) local climatic conditions, and 3) interaction of surface water and groundwater in the area.

Of course, field observations and expert knowledge of the area should also be used in the decision making process. For example, it might be unwise to implement brush control in upland areas that contribute to highly saline springs. Increasing spring flows might simply increase salt loads to downstream rivers and reservoirs. Likewise, land fragmentation or land owner attitudes toward wildlife might reduce the feasibility of implementing large-scale brush control programs in some areas.

These tools are now available to decision makers who wish to estimate the benefits, costs, and most appropriate locations to implement brush management programs in different locations across Texas or within a specific watershed.

A geographically targeted brush control program with careful scientific verification of impacts is needed to guide long-term brush control policies.

Because of large year-to-year variation in rainfall and spatial variation in geology, soils, brush cover, and land ownership, obtaining definitive measurements of the effects of brush control on streamflows and aquifer recharge is

Mechanical-removed brush near San Angelo very challenging. A comprehensive and definitive watershed-scale hydrologic study measuring all relevant components of the rangeland water balance has never been done in Texas. However, in view of the large amounts of water in question and the expectation of continued brush encroachment, such studies have been strongly recommended (Rainwater et al., 2008; Wilcox et al., 2005).

Our scientific understanding of the benefits and costs of brush control have increased dramatically since the Rocky Creek experience in the 1960s and 1970s or the beginnings of the Texas State Soil and Water Conservation Board brush control efforts a decade ago. The methods recently developed by Rainwater et al. (2008) and Srinivasan (personal communication), combined with the economic and hydrologic results of earlier modeling studies conducted for the Texas State Soil and Water Conservation Board brush control program (Texas Agricultural Experiment Station, 2000) should be used to guide a pilot program in carefully selected areas to demonstrate the efficacy of brush control to enhance water yield. The program should be implemented in areas where brush control is most likely to increase water yields, perhaps on juniper-infested upland areas of the Edwards Plateau and riparian bottomlands covered with salt cedar, mesquite, giant cane, and other undesirable species elsewhere in the state. The program should include rigorous scientific verification of the impacts of brush control on runoff, aquifer recharge, spring flows, in-streamflows, rangeland productivity, wildlife habitat, fisheries, the potential to harvest brush for bioenergy production, and landowner attitudes. This scientific information would provide invaluable guidance for future decision makers interested in expanding brush management programs for both water yields and other benefits they produce.

Concluding Remarks

Reaching scientific consensus about the effects of brush management on rangeland water yield has been challenging, complicated by issues of measurement methods, temporal variation of precipitation, and spatial variation in landscape, climate, vegetation, soils, and geology.

In addition to these scientific and technical issues, scientists, landowners, policymakers, and other stakeholders maintain a host of beliefs, both positive and negative, about brush control's effects on water availability. Furthermore, brush management for grazing land and livestock productivity, ecosystem health, wildlife habitat, endangered species habitat, environmental flows, water supplies, carbon sequestration and the landscape's scenic value are also quite important and should be taken into consideration prior to brush control implementation. Perceptions regarding the long-term impacts of climate change, grazing, and fire on vegetation further complicate discussions of brush management.

A few authors have grappled with these complex issues and explored the relationships between multiple factors. For example, Conner et al. (2001) found that the shift from grasslands to woodlands has contributed to an overall decrease in the total amount of grassland habitat and the loss of ecosystem functions while Teague et al, (2008) concluded that a system of brush control using prescribed fire, rotational grazing and grazing deferment can maximize ecosystem health and function simultaneously with land manager profits. Olenick et al. (2004) were able to quantify the monetary benefits of brush removal and found that the public cost of producing additional water ranged from $32 per acre-foot to $159 per acre-foot depending on the location within the Edwards Plateau. These examples only provide a snapshot of brush management's economic benefit. More extensive evaluations will undoubtedly be able to link the economic impacts of ecosystem services to tax revenues and economic activity.

Ultimately, landowners will manage their property as they desire; however, efforts should be made to convey the importance of achieving and maintaining a healthy balance of brush and grasslands to the landowner and society. While removing all brush would likely have more profound impacts on the hydrologic cycle, it would be detrimental to many species that depend on these landscapes for critical habitat. Selectively clearing brush using a set of predetermined criteria such as those set forth by Rainwater et al. (2008) and Srinivasan (personal communication) will likely have the most profound and positive impacts on ecosystem health, rangeland condition, and water salvage while maintaining the ecological integrity of the landscape. It must be stressed that proper management and maintenance of these lands after brush control has been carried out is the most important factor in maintaining the long-term balance, function, and health of the landscape.

For the foreseeable future, Texas landowners will manage their properties with multiple economic, aesthetic, and environmental objectives. Scientists and policy makers should strive to provide these landowners with scientifically based information, education, decision tools, policies and programs to achieve both private and public benefits from Texas’ private lands. Brush control programs are a very important means of managing the state’s private grazing lands to achieve both private and public goals.

Literature Cited

Afinowicz, J. D., C. L. Munster, and B. P. Wilcox. 2005. Modeling effects of brush management on the rangeland water budget: Edwards Plateau, Texas. *Journal of the American Water Resources Association.* 41(1):181-193.

Archer, S. 1994. Woody plant encroachment into southwestern grasslands and savannas: rates, pattern and proximate causes. *Ecological implications of livestock herbivory in the west.* M. Vavra, W. Laycock and R. Pieper (eds.), 36-68. Denver: Society for Range Management.

Arnold, J. G., S. Bednarz, T. Dybala, W. A. Dugas, R. S. Muttiah, and W. Rosenthal. 2008. Rangeland water yield: influence of brush clearing. *Encyclopedia of Water Science.* 955-57. London: Taylor and Francis.

Ball, L. and M. Taylor. 2003. *Brush Management: Myths and Facts. Environmental Defense*. Available online at: http://www.texaswatermatters.org/pdfs/brush_management.pdf.

Bell, G. 1997. Ecology and management of *Arundo donax*, and approaches to riparian habitat restoration in Southern California. J. H. Brook, M. Wade, P. Pysek, and D. Green (Eds.,), *Plant invasions: Studies from North America and Europe* 103-13. Leiden, The Netherlands: Blackbuys Publishers.

Blackburn, W. H. 1983. Influence of brush control on hydrologic characteristics of range watersheds. *Brush Management Symposium, Society for Range Management Meeting*, Albuquerque, NM. 73-88.

Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and ET. *Journal of Hydrology.* 55:3-23.

Carlson, D. H., T. L. Thurow, R. W. Knight, and R. K. Heitschmidt. 1990. Effect of honey mesquite on the water balance of Texas Rolling Plains rangeland. *Journal of Range Management* 43**:**491-96.

Carlson, D. H., and T. L. Thurow. 1996. Comprehensive evaluation of the improved SPUR model (SPUR-91). *Ecological Modelling.* 85:229-240.

Cleverly, J. R., C. N. Dahm, J. R. Thibault, D. J. Gilroy, and J. E. A. Coonrod. 2002. Seasonal estimates of actual evapotranspiration from *Tamarix ramosissima* stands using three-dimensional eddy covariance. *Journal of Arid Environment.* 52:181-97.

Conner, R., A. Seidl, L. VanTassell, and R. N. Wilkins. 2001. *United States Grasslands and Related Resources: An Economic and Biological Trends Assessment*. Texas A&M University. Available online: http://landinfo.tamu.edu/presentations/grasslands.html.

Corbett, E. S., and R. P. Crouse. 1968. *Rainfall interception by annual grass and chaparral…losses compared*. Berkley, CA. Pacific SW Forest and Range Experiment Station. 12pp. US Forest Service Research Paper PSW-48.

Dugas, W. A., and H. S. Mayeux Jr. 1991. Evaporation from rangeland with and without honey mesquite. *Journal of Range Management.* 44(2):161-70.

Dugas, W. A., R. A. Hicks, and P. Wright. 1998. Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed. *Water Resources Research.* 34**:**1499-1506.

Everitt, B. L. 1998. Chronology of the spread of tamarisk in the central Rio Grande. *Wetlands.* 18(4):658-68.

Gatewood, J. S., T. W. Robinson, B. R. Colby, L. C. Halpenny, and J. D. Hem. 1950. Use of water by bottom-land vegetation in the lower Safford Valley, Arizona. Geological Survey Water Supply Paper 1103. U.S. Government. Printing Office, Wash.

Griffin R. C., and B. A. McCarl. 1989. Brushland management for increased water yield in Texas. *Water Resources Bulletin.* 25(1):175-86.

Goodrich, D. C., R. L. Scott, J. Qi, B. Goff, C. L. Unkrich, M. S. Moran, D. Williams, S. Schaeffer, K. Snyder, R. MacNish, T. Maddock, D. Pool, A. Chehbouni, D. J. Cooper, W. E. Eichinger, W. J. Shuttleworth, Y. Kerr, R. Marsett, and W. Ni. 2000. Seasonal estimates of riparian evapotranspiration using remote and in-situ measurements. *Agricultural and Forest Meteorology*. 105:281-309.

Hart, C. R., A. McDonald, Z. Sheng, and L. D. White. 2005. Saltcedar control and water salvage on the Pecos River, Texas, 1999-2003. *Journal of Ecological Management*. 75:99-409.

Hart, C. R. 2005. *Pecos River ecosystem project progress report*. Texas Water Resources Institute, College Station.

Hibbert, A. R. 1983. Water yield improvement potential by vegetation management on western rangelands. *Water Resources Bulletin.* 19(3):375-81.

Huang, Y., B. P. Wilcox, L. Stern, and H. Perotto-Baldivieso. 2006. Springs on rangelands: runoff dynamics and influence of woody plant cover. *Hydrological Processes.* 20:3277-88.

Huxman, T. E., B. P. Wilcox, D. D. Breshears, R. L. Scott, K. A. Snyder, E. E. Small, K. Hultine, W. T. Pockman, and R. B. Jackson. 2005. Ecohydrological implications of woody plant encroachment. *Ecology* 86(2):308-319.

Jackson, R. B., L. A. Moore, W. A. Hoffman, W. T. Pockman, and C. R. Linder. 1999. Ecosystem rooting depth determincal with caves and DNA. *Proceedings of the National Academy of Sciences* 96:11387-11392.

Jackson, N. E., N. E. Katagi, and C. Loper. 2002. Southern California Irrigated Watershed Program: Arundo removal protocol. Santa Ana Watershed Project Authority. http://www.sawpa.org/arundo/ (retrieved March 1, 2007).

Kelton, E., 1975. The story of Rocky Creek. *The Practicing Nutritionist*. 9:1-5.

Knight, R. W., W. H. Blackburn, and C. J. Scifres. 1983. Infiltration rates and sediment production following herbicide/fire brush treatments. *Journal of Range Management* 36(2):154-157.

Lackey, R. T. 2001. Values, Policy, and Ecosystem Health. *BioScience*. 51(6):437-443.

McGinley, S., 2008. Study Finds Silver Lining for Maligned Saltcedars. University of Arizona news release. Oct. 29, http://uanews.org/node/22298.

Miyamoto, S., F. Yuan, and S. Anand. 2005. *Reconnaissance survey of salt sources and loading into the Pecos River*. TWRI Report No. TR-291). College Station, TX: Texas Agricultural Experiment Station: Texas Water Resources Institute.

Moore, G. W., and M. K. Owens. 2006. Removing adult overstory trees stimulates growth and transpiration of conspecific juvenile trees. *Rangeland Ecology & Management* 59:416-421.

Moore, G. W., J. R. Cleverly, and M. K. Owens. 2008. Nocturnal transpiration in riparian Tamarix thickets authenticated by sap flux, eddy covariance and leaf gas exchange measurements, *Tree Physiology* 28:521-528.

Nagler, P. L., E. P. Glenn, K. Didan, J. Osterberg, F. Jordan, and J. Counningham. 2008. Wide-area estimates of stand structure and water use of *Tamarix* spp. on the Lower Colorado River: Implications for restoration and water management projects. *Restoration Ecology* 16:136-145.

Olenick, K. L., J. R. Conner, R. N. Wilkins, U. P. Kreuter, and W. T. Hamilton. 2004. Economic implications of brush treatments to improve water yield. *Journal of Range Management* 57(4): 337-345.

Owens, M. K., G. M. Moore. 2007. Saltcedar water use: realistic and unrealistic expectation. *Rangeland Ecology and Management* 60:553-557.

Owens, M. K., and R. W. Knight, Water use on rangelands. *Water for South Texas*, TAES CPR 5043-5046; College Station, TX, 1992: 1-7.

Qashu, H. K., and D. D. Evans. 1967. Water disposition in a stream channel with riparian vegetation. *Soil Science Society of America Proceedings* 31(2):263-269.

Rainwater, K. A., E. B. Fish, R. E. Zartman, C. G. Wan, J. L. Schroeder, and W. S. Burgett. 2008. *Evaluation of the TSSWCB Brush Control Program: Monitoring Needs and Water Yield Enhancement.* Final Report to Texas Commission on Environmental Quality. Texas Tech University Water Resources, August 2008.

Redeker, E. J., Thurow, T. L., and X. Wu. 1998. Brush management on the Cusenbary Draw watershed: history and ramifications. *Rangelands* 20(15):12-14.

Richardson, C. W., E. Burnett, and R. W. Bovey. 1979. Hydrologic effects of brush control on Texas rangelands. *Transactions of the ASAE.* 22:315-319.

Saleh, A., H. Wu, C. S. Brown, F. M. Teagarden, S. M. McWilliams, and L. M. Hauck, 2008. Effect of brush on evapotranspiration in the North Concho river watershed using eddy covariance technique. (submitted for publication).

Scott, R. L., W. J. Shuttleworth, D. C. Goodrich, and T. Maddock III. 2000. The water use of two dominant vegetation communities in a semi-arid riparian ecosystem. *Agricultural and Forest Meteorology* 105:241-256.

Scott, R. L., C. Watts, J. G. Payan, E. Edwards, D. C. Goodrich, D. Williams, and W. J. Shuttleworth. 2003. The understory and overstory partitioning of energy and water fluxes in an open canopy, semi-arid woodlands. *Agricultural and Forest Meteorology* 114:127-139.

Seyfried, M. S., B. P. Wilcox. 2006. Soil water storage and rooting depth: key factors controlling recharge on rangelands. *Hydrological Processes* 20:3261-3275.

Teague, W. R., W. E. Grant, U. P. Kreuter, H. Diaz-Solis, S. Dube, M. M. Kothmann, W. E. Pinchak, and R. J. Ansley. 2008. An ecological economic simulation model for assessing fire and grazing management effects on mesquite rangelands in Texas. *Ecological Economics* 64:611-624.

Texas Agricultural Experiment Station. 2000. *Brush Management/Water Yield Feasibility Studies for Eight Watersheds in Texas.* (TWRI Report No. TR-182). College Station, TX: Texas Agricultural Experiment Station, Texas Water Resources Institute.

Thurow, T. L., W. H. Blackburn, S. D. Warren, C. A. Taylor Jr. 1987. Ranfall interception by midgrass, shortgrass, and live oak mottes. *Journal of Range Management* 40:455-460.

Thurow T. L. 1990. Brush management potential for increasing water yield from Texas rangeland. *Proc. Brush Management Symposium*. Pleasanton, Texas, May 1990, pp. 25-32. College Station, TX. Texas Agricultural Extension Service.

Thurow, T. L., W. H. Blackburn, S. D. Warren, and C. A. Taylor, Jr. 1987. Rainfall interception by midgrass, shortgrass, and live oak mottes. *Journal of Range Management* 40:455-460.

Thurow, T. L., and C. A. Taylor, Jr. 1995. Juniper effects on the water yield of Central Texas rangelands. *Water for Texas: Research Leads the Way*; Proc. 24th Water for Texas Conference. Austin, Texas, Jan. 1995, pp. 657-665. College Station, TX: Texas Water Resources Institute.

Thurow, T. L., and J. W. Hester. 1997. How an increase or reduction in juniper cover alters rangeland hydrology. In: *Juniper Symposium 1997*, pp. 4:9-22. Texas A&M University Research Station at Sonora. TR 97-1.

Thurow, T. L., A. P. Thurow, and M. D. Garriga. 2000. Policy prospects for brush control to increase off-site water yield. *Journal of Range Management* 53:23-31.

Tromble, J. M., 1972. Use of water by a riparian mesquite community. In: *Proceedings of the National Symposium on Watersheds in Transition*. American Water Resources Association and Colorado State University, pp. 267-270.

Unland, H. E. A. M. Arain, C. Harlow, P. R. Houser, J. Garatuza-Payan, P. Scott, O. L. Sen, and W. J. Shuttleworth. 1998. Evapotranspiration from a riparian system in a semi-arid environment. *Hydrological Processes*. 12:527-542.

Van Auken, O. W. 2000. Shrub invasions of North America semiarid grasslands. *Annual Review of Ecological Systems* 31:197-215.

Wilcox B. P. 2002. Shrub control and streamflow on rangelands: A process-based viewpoint. *Journal of Range Management* 55:318-326.

Wilcox, B. P., M. K. Owens, R. W. Knight, and R. K. Lyons. 2005. Do woody plants affect streamflow on semiarid karst landscapes? *Ecological Applications* 15:127-136.

Wilcox B. P., S. L. Dowhower, W. R. Teague, and T. L. Thurow. 2006a. Long-term water balance in a semiarid shrubland. *Rangeland Ecology Management* 59:600-606.

Wilcox, B. P., M. K. Owens, W. A. Dugas, D. N. Ueckert, and C. R. Hart CR. 2006b. Shrubs, streamflow, and the paradox of scale. *Hydrological Processes* 20:3245-3259.

Wright, P. N. 1996. Spring enhancement in the Seco Creek water quality demonstration project. *Seco Creek Water Quality Demonstration Project*. United States Department of Agriculture, Natural Resources Conservation Service, Temple, Texas.

Wu, X. B., E. J. Redeker, and T. L. Thurow. 2001. Vegetation and water yield dynamics in an Edwards Plateau watershed. *Journal of Range Management.* 54:98-105.

Texas Water Resources Institute
1500 Research Parkway, Suite A240
2118 TAMU
Collge STation, TX 77843-2118
Tel: 979.845.1851 • Fax: 979.845.8554
Email: twri@tamu.edu
http://twri.tamu.edu