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Shrubs, streamflow, and the paradox of scale

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Abstract:

In this paper, we examine the linkage between woody plants and the water budget for three important woody plant communities in Texas, USA: saltcedar (*Tamarix chinensis*, *Tamarix ramosissima*), Ashe juniper (*Juniperus ashei* Buchholz), and mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*). In most cases, these species are found in distinct physiographic and soil settings. Saltcedar is restricted to stream channels and floodplains; Ashe juniper is found mostly on karst limestone outcrops with shallow soils; and mesquite is found on deep soils. Because of these differences, changes in woody plant cover in each community will have a different effect on the water budget. For each type, we review the available literature and explicitly report the scale of observation (tree, stand, catchment, or landscape). A simple framework called the *shrub–streamflow framework*, which recognizes differences in response due to differences in physiographic setting, climate, and potential for deep drainage or subsurface flow, enables us to generalize the results. The fundamental premise of the framework is simple: for shrublands to be hydrologically sensitive to changes in woody plant cover, soil water or groundwater must be accessible to deep-rooting plants but too deep for shallow-rooting ones. Such a situation exists if groundwater is close to the surface (within 3–5 m and/or if deep drainage occurs (because of either high precipitation input or bypass flow in the soil). We argue that on an area basis, conversion of saltcedar stands to herbaceous plants in riparian regions has a much greater potential for increasing water yield than does conversion of woodlands to grasslands in upland regions where deep drainage does not occur. On upland sites where deep drainage does occur, conversion from woody to herbaceous vegetation may result in a savings of 40–80 mm year^{-1} of water. But such savings have been observed only up to the small-catchment scale, and until further work is done it is uncertain whether they can be achieved at larger scales.

KEY WORDS range hydrology; runoff; ecohydrology; water yield; woody plants

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INTRODUCTION

The disparity between water supply and demand is increasing globally and is particularly acute in semiarid climates. For rangelands with a dense cover of woody plants, one potential mechanism for increasing the supply of water is to reduce this cover, and thereby decrease the amount of water consumed. During the last century, both the density and coverage of shrubs have increased dramatically on rangelands across the globe, converting former grasslands or savannas into shrublands or closed-canopy woodlands (Van Auken, 2000). At the same time, flows from springs and rivers have diminished (Brune, 2002). Some argue that the two phenomena are interconnected—i.e. that deep-rooted woody plants are drawing off subsurface water that would otherwise supply baseflow for rivers and springs or become groundwater.

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Although intuitively appealing, the notion that increased woody plant cover on rangelands is linked to diminished water yield (streamflow and recharge) is at present backed by little scientific evidence, particularly for larger scales. It is evidence for the larger scales that is most important, because increased water yield is most relevant to off-site users at these scales. However, most water-use data have been collected at the tree or small-plot scale. Therefore, we often draw conclusions for larger scales by extrapolating from small-scale data—a process that involves some uncertainty. One way to raise the level of confidence in such extrapolation is to compare estimates made at multiple scales.

The relationship between science and policy on the shrub control issue is of particular interest in Texas, where policy makers have been aggressively promoting shrub control as a means for increasing water supply from rangelands. Since 1999, Texas has spent or allocated around $40 million in public funds for shrub control, the primary justification being that water supply on a large scale will be substantially increased (TSSWCB, 2004).

In this paper, we examine the scientific basis for using shrub control as a means of increasing water supply, with an explicit focus on Texas rangelands. Areas having the potential for increasing streamflow and/or recharge through woody plant manipulation we refer to as *hydrologically sensitive* areas. In large part we have organized our examination using a modified version of a hierarchical framework proposed by Huxman *et al*. (2005), referred to herein as the *shrub–streamflow framework*. The premise of this framework is that if we have important information related to physiographic setting, climate, and recharge potential, we can better determine which rangelands are the most hydrologically sensitive (Figure 1).

In addition, we compare the data for several different scales, the results of which highlight what we call the *paradox of scale*: Regardless of community type, at small scales woody plants appear to have a large influence on the water cycle; but for many areas this effect diminishes as the scale of observation increases (low hydrological sensitivity), whereas for others—such as saltcedar stands in riparian areas—a strong signal seems to be maintained from the tree to the landscape scale, indicating high hydrological sensitivity.

THE SHRUB–STREAMFLOW FRAMEWORK

Despite the uncertainties that remain, we are confident of a number of things regarding the connection between woody plants and streamflow. We know, e.g., that this connection becomes stronger as annual rainfall and/or available water increases. There is extensive literature showing that in forests, streamflow increases following a reduction in the number of trees (Bosch and Hewlett, 1982; Stednick, 1996; Zhang *et al*., 2001). For rangelands, however, relatively few studies have shown that streamflow can be increased by reducing the cover of woody plants. In most semiarid regions, the energy available for evaporation of water is sufficiently high that most of the comparatively low amount of precipitation is ‘lost’ to evapotranspiration, regardless of the type of vegetation present. But there are exceptions—a major one being chaparral or eucalyptus woodlands in Mediterranean climates.

Fundamentally, a hydrologically sensitive area is one in which woody plants access water at depths beyond the reach of non-woody plants. The presence of deeper water may be due to groundwater that is relatively close to the surface, precipitation exceeding the storage capacity of the upper soil, or geologic or soil conditions conducive to rapid transport (bypass flow) of water to deeper layers. The shrub–streamflow framework uses these concepts to predict where hydrologically sensitive shrublands might exist.

The first criterion relates to physiographic setting. Hydrologic sensitivity is likely to be stronger where the groundwater table is within a few metres of the surface. In semiarid climates, this characteristic is most common in riparian settings (though it may be found in certain other settings—see Jobbagy and Jackson (2004)). In riparian areas, woody plants can access shallow groundwater directly, thus drawing water that otherwise would supply streamflow. Even so, in most riparian zones a reduction of woody cover may be undesirable from other perspectives (e.g. streambank stability, wildlife habitat, aesthetics, and biodiversity).

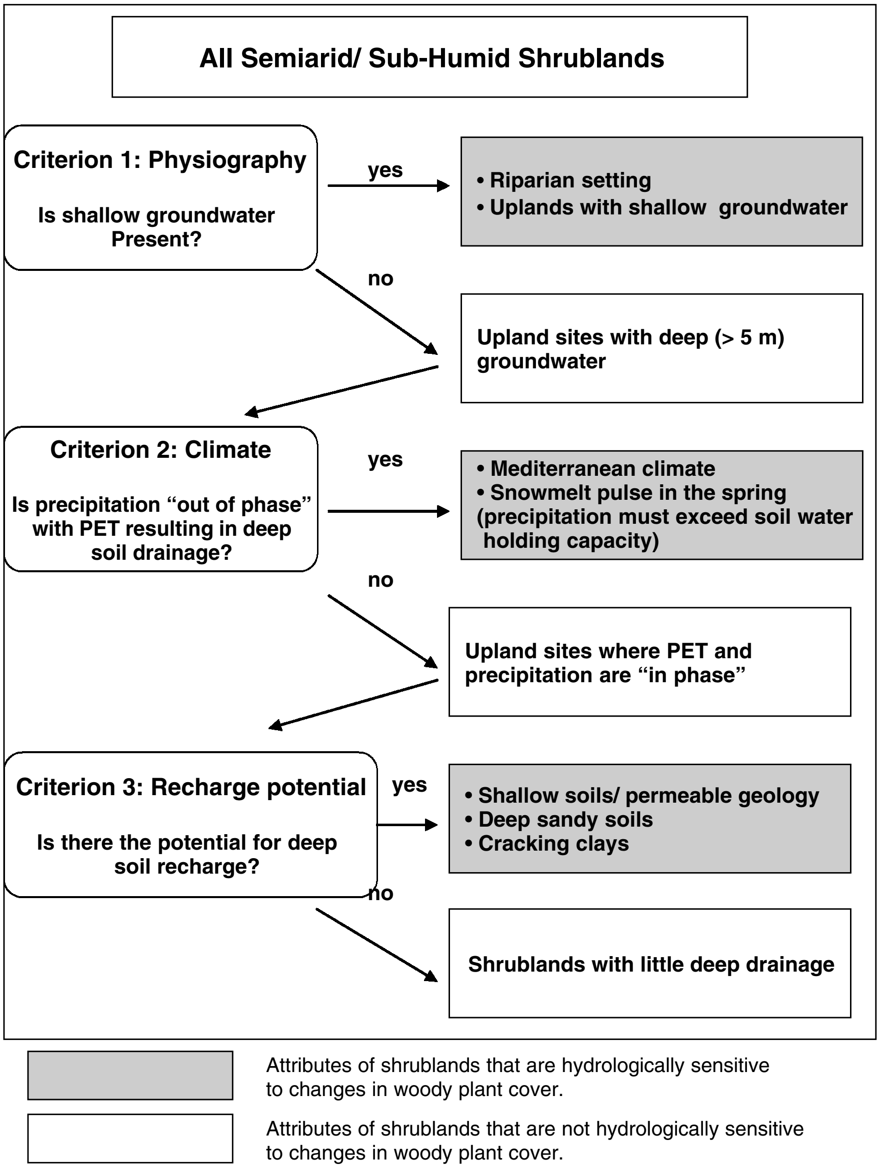

Figure 1. The *shrub–streamflow framework*: classification of the potential for increasing streamflow in various shrublands

The second criterion is related to climate or precipitation regime. In most uplands, hydrologic sensitivity will be strongest where the potential for water to move deeply into the soil—outside the rooting zone of herbaceous plants—is greatest. This characteristic is found in areas where deep drainage occurs because of high inputs of precipitation during the winter. It is no coincidence that the strongest linkage between woody plants and streamflow has been observed in Mediterranean-type climates (those in which precipitation is often 'out of phase' with potential evapotranspiration). For example, in South Africa (Van Wilgen *et al.*, 1996), Spain (Puigdefabregas and Mendizabal, 1998), and Australia (Walker *et al.*, 1993), dramatic changes in streamflow and/or groundwater levels have been observed following vegetation changes in native shrublands. In the United States, the strongest linkages between shrub cover and streamflow are seen in the chaparral

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shrublands of California, which are characterized by Mediterranean-type climates (Hibbert, 1983). In these regions, precipitation occurs mostly in the winter when transpiration is low, and is sufficient to overwhelm the storage capacity of the upper soil, allowing for deeper drainage. Similarly, shrublands in which soil recharge comes mainly from snowmelt may be hydrologically sensitive; a large pulse of melting snow often produces enough water to overwhelm the water storage capacity of the upper soil (Baker, 1984; Seyfried and Wilcox, 2006).

The third criterion is related to soil and/or geologic conditions. Deeper drainage may also result when the soils and geology of a region allow for bypass flow. This characteristic is found, e.g., where soils are shallow and overlie relatively permeable bedrock (such as karst limestones). In such areas, deep drainage and subsurface flow can dramatically exceed what would be expected given the precipitation regime; and intermittent or permanent seeps, springs, and rivers are common—evidence of subsurface water that could be accessed by deep-rooted woody plants. An example in Texas is the Edwards Plateau area, which supports large tracts of juniper woodlands and has considerably more 'flowing water' than would be expected for a semiarid or sub-humid climate (*ca* 700 mm year^{-1}). The explanation lies in the karst geology—a substrate of fractured limestone that allows rapid flow of water to the subsurface. Other soil types that may enable deep drainage are sandy soils and the shrinking–swelling clay soils that develop very deep cracks during the dry season.

If deep water is not available, as is the case for many shrublands, it is unlikely that changes in vegetation cover will affect either recharge or streamflow. In these areas, soils either have sufficient storage capacity to retain, within a metre or two of the surface, most of the precipitation that infiltrates; or precipitation is inadequate to routinely wet the soil at depth. This means that most of the soil water will be available and used by whatever plants are present—woody or herbaceous. Little if any subsurface flow or recharge occurs in these environments (Seyfried *et al.*, 2005).

APPLYING THE SHRUB–STREAMFLOW FRAMEWORK

Texas is home to rangelands that are both vast and diverse, and as has occurred globally, many of the grasslands and savannas have converted to woodlands. Two species of concern are honey mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*) and Ashe juniper (*Juniperus ashei* Buchholz), found in upland areas. Both are native species that have expanded considerably in extent and density, and each has its unique growth pattern and distribution. Honey mesquite is the most extensive, covering large portions of Texas and the southwest. In Texas alone, it covers an estimated 22 million hectares but is mostly restricted to relatively deep soils. Ashe juniper is found mainly on shallow limestone soils, most of which are in the Edwards Plateau region of the state (Scifres, 1980). A third species of concern is saltcedar (*Tamarix chinensis*, *Tamarix ramosissima*), which was introduced as an ornamental and to aid in stabilizing stream banks, and is now the dominant woody plant in many riparian areas in the western part of the state.

There is some confusion and controversy regarding the effects of shrubs on the water budget—primarily because of the lack of data at the landscape scale, which is the scale of greatest interest. In this paper, we summarize our findings for the following spatial scales: (1) individual tree or small plot (the space occupied by a single tree); (2) hillslope or stand (large enough to encompass many trees, and thereby to manifest important hillslope processes such as overland flow, depression storage, and sediment deposition); (3) small catchment (large enough to incorporate channel and groundwater flow processes); and (4) landscape (encompasses watersheds of 20 km^2 or larger).

We apply the shrub–streamflow framework to three distinct geographic regions of Texas rangelands: (1) riparian regions (characterized by accessible groundwater), with emphasis on those dominated by saltcedar; (2) upland regions characterized by deep drainage, highlighting two types—those with karst geology and dominated by Ashe juniper, and those having heavy clay soils with shrink–swell cracking and dominated by mesquite; and (3) upland regions not characterized by deep drainage, with a particular emphasis on honey mesquite. Each of these environmental settings, with its representative vegetation types, is represented in the shrub–streamflow framework (Figure 1) and has been selected to present concepts and examples that have the greatest relevance to Texas rangelands.

Regions characterized by shallow groundwater—riparian zones dominated by saltcedar

To date, most of the research on saltcedar has been conducted in Arizona, California, Nevada, and New Mexico; there has been relatively little research in Texas. Glenn and Nagler (2005) provide a comprehensive review of water use by saltcedar (at the tree and stand scales).

Tree scale. Saltcedar is widely believed to be an extravagant user of water. It has been reported, e.g., that a single saltcedar plant is capable of using over 750 l of water in a day. Although widely cited, such high consumption is highly unlikely; we have been unable to track down any data supporting it. Some studies have inferred high use of water by saltcedar through extrapolation of data beyond the spatial or temporal scale of the measurements—i.e. from short periods of observation to long periods, or from the tree to the stand scale. Extrapolation of this kind can yield very high estimates of water use—as much as 3000 mm year^{-1} (Van Hylckama, 1974; Gay and Fritschen, 1979; Davenport *et al.*, 1982). More recent work, however, indicates that individual saltcedar plants and native riparian woody phreatophytes in the same plant communities use similar amounts of water. Nagler *et al.* (2003), e.g., showed that saltcedar, cottonwood (*Populus* spp.), and willow (*Salix* spp.) trees of similar canopy sizes (4 to 5 m tall) used similar amounts of water on a daily basis (around 50 l day^{-1}). Their conclusion has been supported by other work, including findings of an isotopic study that showed water uptake by saltcedar to be equal to that of native woody plants along the Colorado River (Busch and Smith, 1995). Further, transpiration rates of saltcedar, on a leaf-scale basis, have been shown to be similar to those of other phreatophytes (Sala *et al.*, 1996).

Stand scale. A variety of techniques have been tried to estimate water use by saltcedar at the stand scale, including sap flow measurement, groundwater monitoring, large-lysimeter measurement, and micrometeorology. The results have ranged widely, from 300 to 3100 mm year^{-1} (Gay and Fritschen, 1979; Weeks *et al.*, 1987; Devitt *et al.*, 1998). Such large discrepancies reflect the significant differences in measurement methods, water availability, and stand density.

Micrometeorological techniques, such as the Bowen ratio/energy balance (Devitt *et al.*, 1998) and eddy covariance (Dahm *et al.*, 2002), measure evapotranspiration from the entire plant community, which includes transpiration from all plants and evaporation from the soil. To quantify evapotranspiration for the stand of interest, both methods require measurement over large areas under uniform conditions upwind from the sensors (fetch). Because many riparian communities lack adequate fetch, these techniques may be difficult to properly use. Dahm *et al.* (2002) used eddy covariance to estimate season-long evapotranspiration from several riparian communities along the middle Rio Grande River. They found that saltcedar stands on floodplains had higher evapotranspiration rates (around 1000 mm year^{-1}) than those in non-flooding areas (750 mm year^{-1}) and that evapotranspiration from cottonwood stands was similar to that of the saltcedar stands in non-flooding areas. Devitt *et al.* (1998), also using micrometeorological methods, reported water use for saltcedar stands of 750 mm year^{-1} during a dry year and 1500 mm year^{-1} during a wet year.

Other work at the stand scale likewise indicates that water use by saltcedar is comparable to that of native phreatophytes (Glenn and Nagler, 2005). In many communities, the main physiological variable determining water use at this scale is total leaf area. As indicated by Anderson (1982) and Sala *et al.* (1996), saltcedar would transpire more water than native phreatophytes only when stand densities and/or the leaf-area index are higher—which typically is seen when saltcedar dominates a riparian zone.

Most studies have shown that use of water by saltcedar varies according to the depth of the water table (Van Hylckama, 1970; Carman and Brotherson, 1982; Horton *et al.*, 2001). This implies that saltcedar transpires more water when growing in close proximity to rivers or streams than when growing farther away (Devitt *et al.*, 1997). As stands mature, they develop a dense monoculture that replaces native vegetation; and as stand density and plant size increase, so does water use (Davenport *et al.*, 1982; Sala *et al.*, 1996; Devitt *et al.*, 1997).

Small-catchment scale. No studies have yet been done at this scale.

Landscape scale. Measuring water use by saltcedar (and associated riparian vegetation) for a segment of a stream or river at the landscape scale is a difficult proposition. It entails measuring both water inputs (inflow at the upstream end of the landscape, plus precipitation) and outflows (changes in soil water storage, subsurface flow, and streamflow at the downstream end of the landscape) (Goodrich *et al.*, 2000). Such measurements have been attempted on the Gila River in Arizona (Gatewood *et al.*, 1950; Culler *et al.*, 1982) and on the Pecos River in New Mexico (Welder, 1988).

The Gatewood *et al.* study in Arizona took place in 1943–1944, with the aim of determining how much water could be made available by removing saltcedar. On the basis of comprehensive and very careful seepage runs and inflow–outflow calculations along the river reach, the researchers estimated that a 3760-ha region of phreatophytic vegetation, most of which was saltcedar, was using around 34 million m^3 of water per year (about 920 mm $year^{-1}$), which is in close agreement with the estimates of stand-level water use presented earlier. (Unfortunately, no post-treatment landscape-scale measurements were done, so we have no estimate of how much water would have been 'saved' or whether and to what extent streamflow might have been augmented by removal of the shrubs.)

In a later study (1963–1971) along another section of the Gila River, Culler *et al.* (1982) estimated that water consumption by saltcedar stands was about 1090 mm $year^{-1}$—a very close agreement with the Gatewood study conducted 20 years earlier. In this case, phreatophytes were removed, and subsequent measurements revealed that water savings came to around 480 mm $year^{-1}$ (because replacement vegetation also transpired water). The researchers caution that such amounts of water will be saved only if vegetation is maintained as either cropland or grasses.

The New Mexico study was a large-scale saltcedar control program initiated in 1967 along the 132-km Acme–Artesia reach of the Pecos River. A total of 8700 ha of saltcedar (located 15 m or more from the river) were either bulldozed or root-ploughed. No change in streamflow could be detected as a result of saltcedar clearing, eventhough a companion study (Weeks *et al.*, 1987) found that water use by saltcedar at the stand scale (estimated by the eddy covariance method) was about 300 mm $year^{-1}$ greater than water use by replacement vegetation. Welder (1988) speculates that increases in baseflow may have been masked by a continuing decline in the groundwater contribution to baseflow from the shallow aquifer (due to climate variations and increased groundwater pumping). It is also possible that rapid re-growth of saltcedar and a 'buffer' of untreated saltcedar immediately adjacent to the river was sufficient to maintain evapotranspiration at high levels following treatment.

Upland regions characterized by deep drainage: case 1—karst geology dominated by Ashe juniper

The presence of springs is an excellent indication that subsurface flow exists in a region. On Texas rangelands, springs are most commonly associated with limestone or karst geology. Two important features of such sites—namely, shallow soils (which cannot store much water) and fractured parent material (which allows rapid, deep drainage of rainfall)—facilitate the presence of springs. Rangelands of this type, which in Texas mainly occupy the central part of the state, are typically dominated by Ashe juniper and live oak.

Tree scale. Evergreen shrubs such as juniper have a large capacity for capturing precipitation, not only because they retain their leaves year round, but because they have a high leaf area per tree (Hicks and Dugas, 1998). Owens *et al.* (2006) estimated that the canopy and litter layer of an Ashe juniper tree together intercept about 40% of the precipitation that falls on the tree annually. At the same time, the percentage varied dramatically depending on the size of the storm: close to 100% of the rainfall from small storms ($<$12 mm) was captured by interception, whereas a much smaller percentage (around 10%) was intercepted and evaporated during large storms. Transpiration from an Ashe juniper community should be greater than that from a herbaceous community because Ashe juniper transpires throughout the year, typically has a much greater community leaf area, and can access water at greater depths. Owens and Ansley (1997), on the basis of direct measurement of Ashe juniper transpiration rates, concluded that a mature Ashe juniper tree transpired as much as 150 l day^{-1}, which they estimated would be equivalent to 400 mm year^{-1}.

In summary, dense stands of juniper intercept and transpire large quantities of water. In regions where juniper cover is extensive and dense, therefore, this species can have a major impact on the water cycle at the tree scale. However, because removal of juniper may result in increased growth and density of other vegetation, which would also transpire and intercept water, it is uncertain how much water would be 'saved' by juniper removal. As discussed below, larger-scale studies are required to make such an assessment.

Stand scale. At this scale, the primary measurements of evapotranspiration have been direct estimates made by means of micrometeorological technology. We know of only one such study for Ashe juniper communities: Dugas *et al.* (1998) measured evapotranspiration from an Ashe juniper community using the Bowen ratio/energy balance method. Two paired areas, each 200×600 m in size, were selected for measurement over a 5-year period. After the first 2 years, all Ashe juniper trees were removed from one of the areas by hand cutting and burning. For the 2-year period following this treatment, the difference in evapotranspiration between the two areas was about 40 mm year^{-1}; but this treatment effect disappeared in the third year of the study, after which evapotranspiration was similar in the treated and untreated areas.

Small-catchment scale with springs: Over the past 150 years, many springs in Texas have dried up, perhaps owing to increased groundwater pumping (Brune, 2002) and/or the spread of woody plant cover. There are many anecdotal accounts of springs drying following the encroachment of woody plants, and of spring flow returning after woody plant cover was removed or reduced. Increases in discharge from springs or spring-fed catchments following the removal of Ashe juniper have been documented in two studies. Wright (1996), working on a 3-ha catchment in the Seco Creek Watershed of central Texas, reported an increase in spring flow, from 11·8 l min^{-1} during the 2-year pre-treatment period to 14·3 l min^{-1} following partial removal of Ashe juniper—this despite the fact that precipitation was lower in the post-treatment period. This increase in flow translates to about 40 mm year^{-1} of additional water. Similarly, Huang *et al.* (2006) estimate that runoff from a small spring-fed catchment increased by about 45 mm year^{-1} following removal of Ashe juniper from around 60% of the catchment.

Small-catchment scale without springs: A few studies have examined the effect of juniper removal on small catchments where no springs were present. Richardson *et al.* (1979) compared runoff from two 3·7-ha catchments for an 11-year period. Juniper was removed from one of the catchments in the fifth year by root. Surface runoff (presumably generated as Horton overland flow) was about 20% (13 mm year^{-1}) lower following this treatment, but this was attributed to increased surface roughness that enhanced surface storage. In another paired-catchment study (in the Seco Creek watershed), Dugas *et al.* (1998) found that when juniper cover was removed by hand cutting, the treatment had little influence on surface runoff from these small (6- and 4-ha) catchments. Runoff accounted for about 5% of total precipitation and occurred only when precipitation intensity was high. Similarly, Wilcox *et al.* (2005) concluded that changes in density of Ashe juniper had little influence on streamflow from small catchments in the western portion of the Edwards Plateau.

Landscape scale. For Ashe juniper rangelands, no large-scale experiments have been conducted. However, we may be able to infer information from analysis of historical streamflow.

Streamflow data going back to the early 1900s are available for many of the major rivers in Texas. These long-term data can provide insight into the nature and variability of streamflow and the relationship of streamflow to climate. In addition, such records may shed light on the sensitivity of streamflow to landscape-scale changes in vegetation cover. For example, we have good evidence that woody plant cover on the Edwards Plateau increased dramatically during the last century (Smeins *et al*., 1997). Therefore, if there is indeed a strong connection between streamflow and woody plant cover, we should be able to detect a decrease in streamflow that is independent of precipitation differences.

To date, only a few attempts at such analysis have been made for the Edwards Plateau. One of these studies, by the Lower Colorado River Authority, examined flow from 1939 to 2000 on one of the major rivers in the region, the Pedernales, which drains an area of over 2300 km^2 (LCRA, 2000). The results showed no evidence of changes in streamflow that were independent of changes in climate during this period. If woody plant cover has increased in this basin, as it has throughout much of the Edwards Plateau (Smeins *et al*., 1997), then these results would indicate that at very large scales, rivers are relatively insensitive to changes in woody plant cover. Unfortunately, since there has been no detailed assessment of vegetation change in the Pedernales basin, we cannot definitively say to what extent woody plant cover has changed during the last 60 years—if it has changed at all.

Upland regions characterized by deep drainage: case 2—heavy clay soils with shrink–swell cracking and dominated by mesquite

Some mesquite rangelands in which deep drainage does occur and/or groundwater tables are accessible to woody vegetation are likely to be hydrologically sensitive as well. One study supporting this assertion was carried out by Richardson *et al*. (1979) to evaluate the hydrologic consequences of removing mesquite on the Blackland Prairie of Texas. The study is an important one—both because it is very comprehensive and because it is widely cited as evidence that mesquite removal, irrespective of location, will increase recharge and streamflow.

The Blackland Prairie of Texas is an important ecoregion that is now largely under intensive agricultural production. However, some areas remain native rangelands with vegetation that includes mesquite. Soils in the Blackland Prairie are typically fine, montmorillonitic clays that have a high shrink–swell potential. When dry, these soils develop extensive cracking that allows rapid and deep movement of any rainfall that occurs. Once wet, however, their permeability is much reduced and allows only slow transit of water.

The Richardson *et al*. (1979) study tracked changes in soil moisture and surface runoff over a period of 7 years in a pair of small catchments where the average annual precipitation was 860 mm. Monitoring of soil water to a depth of 1·5 m suggested that following mesquite removal, evapotranspiration was lower and soil moisture higher (by about 80 mm year^{-1}). Further, the researchers found that surface runoff increased by about 30 mm year^{-1}, which they attributed to generally wetter soil conditions. Surface runoff from these high-clay soils is substantial, averaging about 30% of the water budget.

Results from the Richardson *et al*. (1979) study at first appear to be in conflict with other work on mesquite rangelands, but upon reflection we see that they are consistent with the logic laid out in the shrub-streamflow framework. If the geologic conditions allow water to move beyond the upper soil zone, there is a greater probability that the site will be hydrologically sensitive to changes in woody plant cover. Although no data are yet available, we could make the case that other mesquite rangelands (e.g. in topographically low areas where water collects, or in riparian areas with water tables accessible to woody plants) would be hydrologically sensitive as well.

Upland regions not characterized by deep drainage—focus on mesquite

Streams exhibiting any baseflow are not the norm for most woodlands, shrublands, and savannas in semiarid climates. For these settings, subsurface flow of water is typically minimal, because the upper soil zone has the capacity to store most of the precipitation that occurs. A high percentage of the total annual stream discharge is produced by large storms—conditions under which the presence or absence of shrubs probably has little influence on the amount of runoff.

Of the many woodland types that do not support springs or intermittent streams, we examined mesquite woodlands growing in upland (nonriparian) settings where deep drainage does not typically occur. This woodland type occupies large portions of Texas and the Southwest.

Tree scale. Interception by mesquite amounts to between 15% and 30% of ambient rainfall (Navar and Bryan, 1990; Desai, 1992; Martinez-Meza and Whitford, 1996)—a much smaller percentage than found for juniper. Besides being deciduous, mesquite trees have flat, waxy leaves that are much less effective at holding water than the scale-like leaves of juniper. In addition, the leaf area of a mesquite tree is much less than that of a juniper. Interception by mesquite canopies is about the same as that by herbaceous vegetation (Thurow *et al.*, 1987).

Water use by mesquite depends on a number of factors, including leaf area, density of trees, and water availability. On mesquite sites in North Texas where deep water was not available, Ansley and co-workers found that mesquite relied on shallow soil water (Ansley *et al.*, 1990; Ansley *et al.*, 1992a; Ansley *et al.*, 1992b). Other work in the same area indicates that an individual mesquite tree is capable of using anywhere from 30 to 200 $\mathrm{l\ day^{-1}}$ (Ansley *et al.*, 1991; Ansley *et al.*, 1994; Ansley *et al.*, 1998). Under conditions of limited moisture, trees may decrease transpiration rates by 35% to 75% (Wan and Sosebee, 1991; Dugas *et al.*, 1992). With respect to density, mesquite trees in an open savanna used much more water per tree than comparable trees in dense stands.

Stand scale. At the stand scale, two soil-water-budget studies have been conducted. At a Rolling Plains site where average annual precipitation was 635 mm, mesquite eradication had at the most a minimal effect on soil moisture (Carlson *et al.*, 1990). By inference, removal would not affect community-level evapotranspiration either—largely because of the flush of herbaceous growth following mesquite removal (Heitschmidt and Dowhower, 1991). The other study took place in an area of south Texas where the average annual precipitation was 710 mm. Weltz and Blackburn (1995) found little difference in soil moisture storage or evapotranspiration between adjacent mesquite- and grass-dominated communities.

Evapotranspiration by mesquite has also been studied at the stand scale at two other Rolling Plains sites. Dugas and Mayeux (1991) eradicated mesquite on one of the sites (the other was left untreated), and then used the Bowen ratio/energy balance technology to measure evapotranspiration. The results showed that under dry conditions, evapotranspiration from the untreated site was somewhat greater than from the treated site; but under wet conditions there was no significant difference. The small difference between the two sites again was attributed to the vigorous growth of herbaceous vegetation following mesquite eradication on the treated site—a phenomenon noted by many other researchers documenting the effects of mesquite control in various areas of Texas (Dahl *et al.*, 1978; Heitschmidt *et al.*, 1986; Heitschmidt and Dowhower, 1991). Dugas and Mayeux (1991) concluded that ‘under circumstances of low grazing pressure and low runoff potential, honey mesquite removal would provide little if any additional water for off-site uses in the short term.’

Small catchment and landscape. No studies have yet been done at these scales.

DISCUSSION

In this paper, we have presented our evaluation of the hydrologic sensitivity of some important woodland types in Texas, using the shrub–streamflow framework as an organizing structure. The woodland types we have delineated are (1) shrublands where physiographic factors make groundwater accessible to woody plants—a prime example being riparian settings dominated by saltcedar; (2) shrublands where deep drainage may occur because of soil and/or geologic conditions—examples being regions having karst geology that are dominated by Ashe juniper, and regions having clay soils that form deep cracks when dry and that are dominated by mesquite; and (3) shrublands where deep drainage is relatively unimportant—often populated by mesquite. We have been explicit about the scale of observation as well as the methods of measurement. On the basis of this evaluation, we now present some comparisons across scales and across sites.

Saltcedar—riparian zones

Compared with other woody plant types, saltcedar has been quite thoroughly studied, which enables us to make a more comprehensive analysis. We have compiled most of the studies that estimate water use by saltcedar and arranged them according to scale of observation, environmental conditions, and methodology used. For ease of comparison, estimated water use by saltcedar is expressed in mm year^{-1}. For those studies reporting in other units, we converted the data to mm year^{-1} by assuming (1) a growing season of 192 days (Cleverly *et al.*, 1997) and (2) a sap wood area of 0·0031 m^2 m^{-2}. (We calculated the latter from measurements on a saltcedar stand on a middle Rio Grande floodplain; this stand had a density of about 26 300 stems/ha and a tree height of about 3·5 m [unpublished data].)

Using the comparison data from the various studies, we created the box diagram in Figure 2. It is important to emphasize that these results represent 'water use' rather than 'water savings.' Water savings would be the difference, if any, between the amount of water used by saltcedar and the amount used by whatever vegetation replaces it.

The environmental conditions were specified as either wet (spring growth season, very shallow water tables, and/or presence of a stream) or dry (late summer season, desert-edge location, deeper water tables, absence of streams) for each scale of observation. With the results cast in this way, it is obvious that although saltcedar shows considerable variability in water usage, as reported by the different studies, its water use across scales is remarkably consistent.

Under dry conditions, reported variations in water use were low at both the stand and tree scales. But when the environment was wet, both the amount of water used and the variability of usage increased (the latter may be attributed to the wide range of plant densities and water table depths among the study sites).

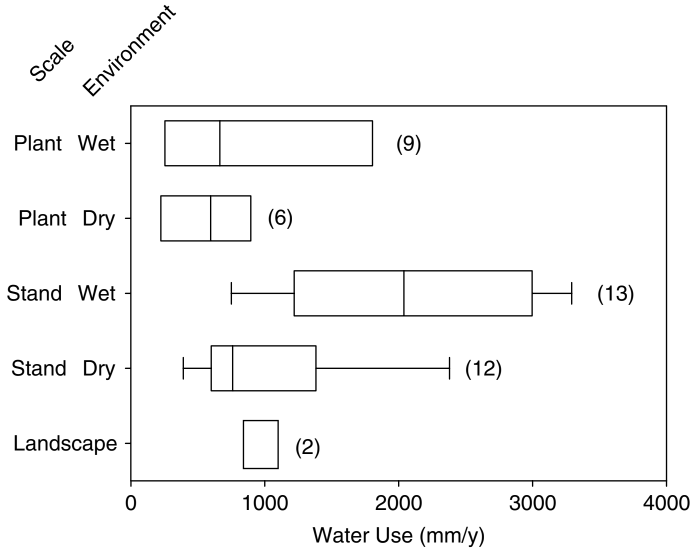

Figure 2. Box-and-whisker diagram showing median, 10th, 25th, 75th, and 90th percentiles for measured water use by saltcedar-dominated phreatophytic vegetation at the tree, stand, and landscape scales. The numbers in parentheses represent the number of studies used. The values for the plant scale represent transpiration only, while the values for the stand and landscape scales reflect total evapotranspirtation (interception, transpiration, and soil evaporation)

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The highest estimates of water use are at the stand scale under wet conditions, with peak values over three times that measured at the landscape scale. The landscape-scale measurements are an integration of both wet environments near riparian areas and dry environments in which the water table may be slightly deeper. It is significant that even at this scale a water-use signal is present—reinforcing the premise that saltcedar riparian stands are hydrologically sensitive areas.

As the data have come in, the consensus has grown that replacement of saltcedar by other woody plants will produce relatively little in water savings (Glenn and Nagler, 2005), whereas replacement of saltcedar with herbaceous plants may result in water savings as high as 500 mm year^{-1}.

Ashe juniper—regions with deep drainage

Much less information is available for Ashe juniper than for saltcedar, but we have enough to make some interesting observations. The influence of Ashe juniper on the water budget remains the subject of some confusion and disagreement, in part because the implications of the scale at which measurements were made have not been fully considered. For example, at the tree scale, the most common measurement is some index of evapotranspiration by trees. After the removal of trees, these numbers have often been extrapolated up without taking into account the compensatory effects of re-growth of trees or replacement by other vegetation.

As highlighted in Figure 3, the tree-scale measurements show very clearly the large effect that juniper exerts on the water budget. But these measurements do not take into account water use by replacement vegetation, as the larger-scale studies do. At the tree scale, for an area with an average annual precipitation of 750 mm year^{-1}, an individual tree will intercept and transpire virtually all of the available water. At the stand scale, however, as estimated by Dugas *et al.* (1998), the difference in water consumption between a woodland and a grassland is only about 40 mm year^{-1}. Similarly, results available at the small-catchment scale (where springs exist) indicate water savings of the same general magnitude (Huang *et al.*, 2006).

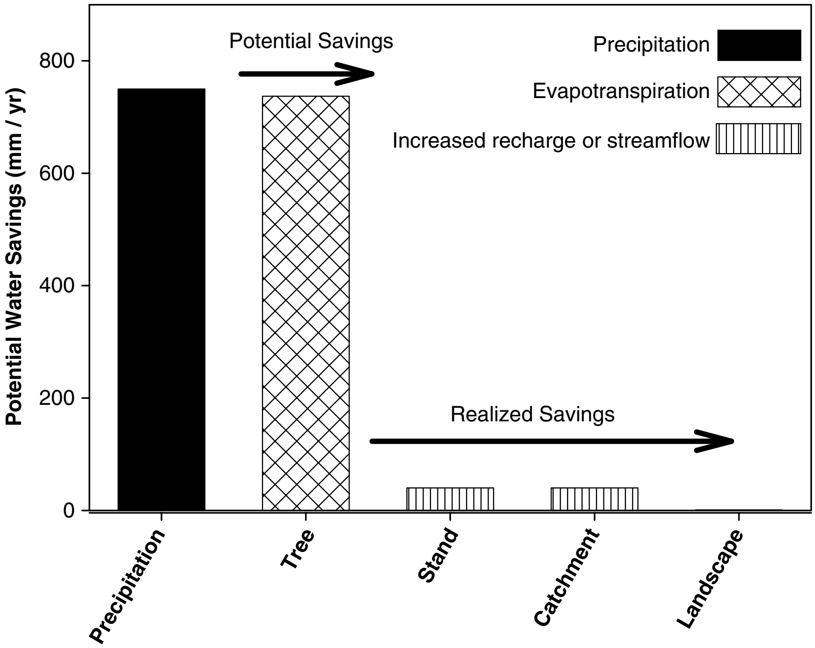

Figure 3. Hypothetical potential and realized savings of water on Ashe juniper rangelands with annual average precipitation of 750 mm year^{-1}. At the tree scale, the bar represents combined water use via interception and transpiration. At the stand, catchment, and landscape scales, the values represent the measured water savings (increases in recharge and/or streamflow) following the removal of Ashe juniper

From these results, we are increasingly confident that conversion of Ashe juniper woodlands to grasslands or more open savannas will translate to increases in spring flow and/or groundwater recharge at the small-catchment scale. But it remains uncertain whether similar results will be seen at larger scales. At the landscape scale, we have not found evidence of water savings due to changes in vegetation cover. The reason for this lack of evidence is not yet clear—whether (1) there has been no net change in woody plant cover; (2) there has been a change in woody plant cover but this has no influence on streamflow; or (3) there has been a change in woody plant cover and it has affected streamflow, but the signal cannot be detected because of too much 'noise' in the data.

Mesquite—regions without deep drainage

Mesquite woodlands may be found in a variety of settings but are most common in areas with relatively deep soils. A few of these soil types are conducive to deep drainage—if they are in topographic lows where water collects or, as in the case of the Blackland Prairie, they are prone to cracking (which can facilitate bypass flow and deep soil recharge). In most mesquite woodlands, however, deep drainage conditions are rare.

We have comparatively little information concerning water use by mesquite, especially at the larger scales. Only one study has been done at the small-catchment scale, at a site in the Blackland Prairie, where the soils exhibit cracking and allow for deep drainage. The results lead to the conclusion that mesquite woodlands in this type of setting are hydrologically sensitive, at least at the small-catchment scale (without actual data, we cannot say to what extent the same would be true for the landscape scale).

But because most mesquite woodlands are found in areas where there is little deep drainage (deep soils and groundwater tables not accessible to trees), we believe that, as a general rule, water savings from reducing mesquite cover would be minimal at best. Even at the smaller scales such an effect is barely measurable.

SUMMARY AND CONCLUSIONS

We have attempted to summarize the current state of knowledge concerning relationships between woody plant or shrub cover and streamflow, for Texas rangelands in particular. By organizing the results of various studies according to the shrub–streamflow framework (Figure 1) and the scale of observation, we can make sense of many apparently contradictory results.

The framework predicts that in Texas, the regions with the highest probabilities of seeing increased water yield from brush control are riparian ones dominated by saltcedar (which would be replaced by herbaceous plants). The fundamental controlling factor seems to be the availability of groundwater. Where saltcedar stands are dense, extensive, and close to a waterway or shallow groundwater source, removing saltcedar and replacing it with nonwoody native plants will result in less overall water use. One such region in Texas is along the Pecos River—where a gallery forest was not present before the invasion of saltcedar and where grasses would dominate after saltcedar removal. Natural grasslands and scattered woody plants along a river would no doubt use less water than saltcedar trees, given the lesser leaf area, shallower rooting depths, and shorter season of active growth.

Our review of the literature suggests—in accord with the framework—that the regions in Texas having the second highest potential for increasing water yield by reducing woody plant cover are upland areas where conditions allow for some deep drainage. The idea is relatively simple. For an upland area to be hydrologically sensitive to changes in woody plant cover, there must be a reservoir of water available to deep-rooting plants that is not available to more shallow-rooting plants. For locations not characterized by groundwater within a few metres of the surface, the geologic conditions must allow deep drainage to maintain these reservoirs. Examples are the relatively mesic rangelands (mainly of Ashe juniper) situated on karst geology and the mesquite woodlands on clay soils that are prone to cracking. On a unit-area basis, when compared with riparian areas of dense saltcedar, water savings in these upland environments are likely to be meager—perhaps 40–80 mm year^{-1}. But this difference is offset by the extensive nature of these woodland types. At present, however, we do not have evidence of higher streamflow or recharge at the landscape scale for either type. Additional field research is needed to determine the extent to which specific rangelands in this category have the potential for increased water yield following shrub control.

Finally, the shrub–streamflow framework predicts that rangelands in which most of the precipitation is retained in the upper 1 m of soil and groundwater is not accessible to woody plants are unlikely to see changes in either streamflow or recharge as a result of changes in the density of woody plants. And indeed, the literature shows no evidence to the contrary. The reason for this is simple: most of the water stored in the soils will be used by whatever vegetation is growing on the landscape. Most of the semiarid shrublands in Texas fall into this category.

On the basis of our review and careful consideration of the issues involved, we believe that the focus of future work should be broadened, from 'brush control for increasing water yield' to 'best management practices for watershed health and sustainability.' The encroachment of woody plants is only one of many ecological changes that have affected the vegetation and hydrological conditions of Texas watersheds. These conditions, and the partitioning of water within the hydrological cycle, are determined by complex interactions between soil and vegetation factors. Clearly there are cases—such as headwater streams fed by springs, and riparian areas dominated by invasive phreatophytes—in which the integration of brush control with other best management practices has the potential to enhance baseflow. It is unclear, however, under what conditions any increased baseflows will translate to greater streamflow in our larger rivers.

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