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Transpiration and Multiple Use Management of Thinned Emory Oak Coppice

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Abstract

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The effects of thinning Emory oak (*Quercus emoryi*) coppice on transpiration have been estimated by the heat-pulse velocity (HPV) method. Rootstocks of trees harvested for fuelwood were thinned to one, two, or three dominant stump-sprouts or left as unthinned controls. Differences in transpiration rates of the thinned coppice were found for each treatment and the control. Earlier research has also shown that thinning of Emory oak stump-sprouts influences the growth and volume of the residual coppice and its value for wildlife habitats. Therefore, a decision matrix is presented to help in the management of thinned Emory oak coppice for optimal combinations of water, wood, and wildlife benefits.

Keywords: Emory oak, coppice, stump-sprouts, transpiration, multiple-resource management

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Introduction

Emory oak (*Quercus emoryi*) woodlands of the Southwestern United States are a valuable resource. People utilize these ecosystems for wood products, grazing cattle, and recreational purposes (Ffolliott 1999, 2002, McClaran and McPherson 1999). The woodlands also protect watersheds from excessive soil erosion and provide a diversity of wildlife habitats for resident and migratory species. However, obtaining these multiple uses of the Emory oak woodlands in an effective ecosystem-based manner can lead to potential conflicts on how the woodlands should be managed. It is necessary, therefore, that resource managers' understanding of the ecological and hydrological processes in these woodlands be at an advanced enough level to holistically manage the woodlands as a sustainable resource.

Our study was designed to determine how the transpiration by rootstocks of thinned Emory oak stump-sprouts (coppice) resulting from earlier harvests of fuelwood responds to thinning treatments of varying intensities. This information complements the findings from an earlier study of the transpiration rates of mature (60 years and older) Emory oak trees and stump-sprouts following selected harvesting of oak trees for fuelwood (Ffolliott and Gottfried 2000, Ffolliott and others 2003). Collectively, this information helps determine the amount of water that is lost by transpiration, the largest component other than precipitation in the water budget for Emory oak woodlands (Ffolliott 2000). We also present a decision matrix that combines the results of this current study and earlier hydrological and ecological studies to help in determining how managers might optimize water, wood, and wildlife benefits from the Emory oak woodlands.

Background

Emory oak is a drought-deciduous species found at the intermediate elevations of mountains in the Southwestern United States. It is found in relatively open stands varying in densities of less than 10 to over 100 trees per ha. Regeneration of Emory oak is mostly in the form of stump-sprouts on the rootstocks of harvested trees (Borelli and others 1994, Ffolliott 1999, 2002). These sprouts arise from dormant buds at the base of a cut stem and provide a mechanism for the species to quickly regenerate itself because of the established rooting system. Growth of the stump-sprouts can be influenced through coppice management including thinning treatments to sustain and, when it becomes necessary, regenerate Emory oak woodlands. Thinning of Emory oak coppice also has the potential of affecting other multiple use benefits.

Earlier hydrological studies related to prescribing management practices for the woodlands have focused largely on determining how transpiration by mature Emory oak trees and stump-sprouts is impacted by different silvicultural treatments. Transpiration is the component of the water budget that in general is most easily altered by vegetative management practices (Brooks and others 2003, Chang 2003). It has been found that mature Emory oak trees in unharvested stands transpire about 45 percent of the annual precipitation falling on the site (Ffolliott and Gottfried 2000, Ffolliott and others 2003). In comparison, nearly 80 percent of the annual precipitation is transpired in stands that have been partially harvested for fuelwood and, as a consequence, are stocked by a residual of mature trees and numerous sprouts arising from the stumps of harvested trees. Even though the transpiration rate of a single stump-sprout is significantly less than that of a mature tree, the greater transpiration by Emory oak in the harvested stands is attributed to the large number of actively growing stump-sprouts. It is apparent, therefore, that harvesting Emory oak trees alters the water budget of a site by reducing the amount of water available for herbaceous plant growth, streamflow and groundwater aquifer recharge, and wildlife inhabitants.

Description of Study

Our objective was to expand the knowledge on the hydrological characteristics of Emory oak woodlands by analyzing the response in transpiration by rootstocks of thinned postharvest coppice. Information obtained from this and the earlier study of transpiration will help to make calculations and simulations of water balances in the woodlands more accurate because measured values of transpiration are available. Managers can then determine the relative amounts of streamflow, soil water storage, and groundwater recharge that might be expected with alternative thinning prescriptions of Emory oak coppice.

Study Area

The study area was in the Coronado National Forest of southeastern Arizona along the United States-Mexico border. It was situated on a south-facing slope of the Huachuca Mountains, approximately 1,750 m in elevation. Casto soils in the Casto-Martinez-Canelo association characterize the area. These soils have been formed from old alluvium and are made up of sedimentary and igneous rocks. Hendricks (1985) describes the soils as having a clayey texture with slow permeability and containing excessive amounts of rock fragments. The 20-year (1980 to 1999) mean annual precipitation in the Huachuca Mountains was 541 ± 32.0 (mean ± standard error) mm. Annual precipitation amounts during the 3-year study were 778 mm in 2000, 544 mm in 2001, and 423 mm in 2003.

Coppice Thinning Treatments

A partial fuelwood harvest of 60 to 75 percent of the mature Emory trees was carried out on the general study area in 1981 as part of the former fuelwood management program of the Sierra Vista Ranger District. Stump-sprouts on rootstocks of the harvested trees were subsequently thinned to one, two, or three of the dominant sprouts in 1984 (Bennett 1988, 1990, Touchan and Ffolliott 1999, Farah and others 2003). A total of 16 rootstocks representing each of these thinning treatments, and an unthinned control were selected for measurement in this study of transpiration (fig. 1). The thinned stump-sprouts had approximately 20 years of postharvest growth at the beginning of this study in June 2000.

Estimating Daily Transpiration Rates

We used the heat-pulse velocity (HPV) method to estimate transpiration rates. This method is based on measurements of the elapsed time between the injection of a heat pulse and detection of the heat wave carried for a precise distance in the water-conducting tissue of a tree (Swanson 1972, Swanson and Whitfield 1981). The heat pulse is injected into the sap stream at a point on the stem (fig. 2). Measurements of this tracer are then made with thermistor probes both upstream and downstream from the source. The net upward velocity of sap represents an index of the instantaneous transpiration rate of the tree. Cross-sectional area through which sap is actively flowing

Figure 1—Rootstocks of thinned and unthinned Emory oak coppice on the study area.

Figure 2—Measuring the heat-pulse velocity of an Emory oak stump-sprout with the sap-flow meter. The thermistor probes are connected to the control unit, which houses the sensitivity gauges, electrical balance indicator, and batteries.

(the sapwood) is calculated from measurements of tree diameter outside the bark, average bark thickness of the stem, and average sapwood width to estimate fluxes of transpiration through time. Average sapwood width was obtained from increment cores. Thorough reviews of the theory, instrumentation, and techniques of thermal methods for measuring sapflow in trees (including the sapflow velocity method) are presented by Swanson (1994), Cohen (1994), and Schaeffer and others (2000).

A modified sap-flow meter originally described by Swanson (1962) was used to obtain HPV measurements necessary to estimate instantaneous transpiration rates of the thinned Emory oak coppice on a biweekly measurement schedule from June 2000 to September 2002. Two exceptions to this schedule were late May through August 2001, when researchers were not available to obtain the measurements, and June to the middle of July 2002, when high fire danger restricted access to the study area. Daily transpiration rates of the stump-sprouts were estimated from the equations of Barret and others (1995) and Schaeffer and others (2000). Estimates of the daily transpiration rates by the rootstocks sampled were obtained by multiplying the daily transpiration rates of the measured stump-sprout(s) on the rootstock by the number of stump-sprouts on the rootstocks for that thinning treatment. The transpiration data for each measurement date were averaged for the three thinning treatments and the control.

We used an analysis of variance to determine if there were significant differences in the average daily transpiration rates among the thinning treatments for the sampling period. A test of homogeneity of variances made before conducting the analysis indicated that the variances of the different samples were heterogeneous. Therefore, we used Dunnett's T3 procedure to provide multiple comparisons that maintain the Type I error when variances are heterogeneous (Dunnett 1980). The level of significance for these tests was 5 percent. Only statistically significant differences are reported here.

Estimating Annual Transpiration on a Stand-Basis

Predictive equations have been developed to estimate the annual transpiration by rootstocks of thinned Emory oak coppice and mature Emory oak trees (obtained by summing the estimated daily transpiration rates for a 12-month period) from measurements of diameters at the root collar of the trees and stump-sprouts (Ffolliott and others 2003 and this study). These equations were solved in terms of the densities of the thinned and unthinned rootstocks, and the mature trees remaining in the stand were sampled to estimate the annual transpiration on a stand-basis following the procedures of Hatton and I Wu (1995), Jarvis (1995), Granier and Breda (1996), and Cermak and Nadezhdina (1998). The amount of precipitation lost to transpiration was estimated on a stand-basis for the thinning treatments in the calender year 2001, the year nearest to the 20-year annual precipitation average.

Results and Discussion

Daily Rootstock Transpiration Rates

Minimum, average, and maximum daily transpiration rates for the three thinning treatments and the unthinned control are presented in table 1. All of the differences in the average daily transpiration rates were significant. Rootstocks thinned to one stump-sprout transpired the least amount of water, with an average transpiration rate of 7.33 ± 0.269 (mean ± standard error) L/day during the 28-month study period. The unthinned control, with an average of 4.5 dominant stump-sprouts per rootstock, transpired the largest volume of water during the study, 32.9 ± 1.17 L/day. Daily transpiration rates for the rootstocks thinned to two and three stump-sprouts were intermediate to these two values.

The trends in average daily transpiration by the thinned rootstocks and control for the study period are illustrated in figure 3. Transpiration in the late summer generally increased following cessation of the summer monsoon seasons that are generally characteristic of southeastern Arizona, when the availability of soil moisture on the study area is also increased. The high values observed in late fall 2000 were attributed to the large storms in October (see below). Low values in transpiration were associated with the late spring-early summer droughts occurring in the two study years, when the drought-deciduous Emory oak trees shed their leaves. The coppice did not become completely dormant in the periods of leaf loss and, therefore, continued to transpire at low rates. A factor that could have affected the transpiration process in drought periods was the ability of the stump-sprouts to sequester water from an extensive interconnected root system. New leaves were fully developed within the month following the initiation of the monsoon summer rains. Overall variations among the calculated daily transpiration rates might have been caused by changes in solar radiation, air temperature, relative humidity, and/or wind speeds over the course of a day of sap-flow measurement.

Daily transpiration rates tended to increase following relatively large precipitation events. An increase in transpiration after the large storms in October 2000 illustrates this response (fig. 4). The lag between a precipitation event and an increase in transpiration likely reflects the time necessary for rain water to infiltrate and percolate to soil depths accessible to the established rooting system (Ffolliott and Gottfried 2000, Ffolliott and others 2003).

Annual Transpiration on a Stand-Basis

Annual transpiration by the rootstocks thinned to one stump-sprout for the selected study year was 67.9 mm, the rootstocks thinned to two stump-sprouts was 160 mm, and the rootstocks thinned to three stump-sprouts was 215 mm. Annual transpiration of the control rootstocks was 320 mm. These findings were coupled with estimates of annual transpiration of the mature Emory oak trees (Ffolliott and Gottfried 2000, Ffolliott and others 2003) remaining on the study area after the fuelwood harvest of 1981 to generate the scenarios of annual transpiration by stands of thinned Emory oak coppice presented in table 2. These estimates were derived by applying the extrapolation

Table 1—Minimum, average, and maximum values and standard errors of daily transpiration rates by rootstocks of thinned Emory oak coppice and the unthinned control.

Transpiration	Thinning treatment			
	One sprout	Two sprouts	Three sprouts	Control
	L/day			
Minimum transpiration per rootstock	4.12	9.30	11.2	19.4
Daily average transpiration per rootstock	7.33 ± 0.269	17.2 ± 0.635	23.0 ± 0.972	32.9 ± 1.17
Maximum transpiration per rootstock	12.6	29.1	36.1	52.0

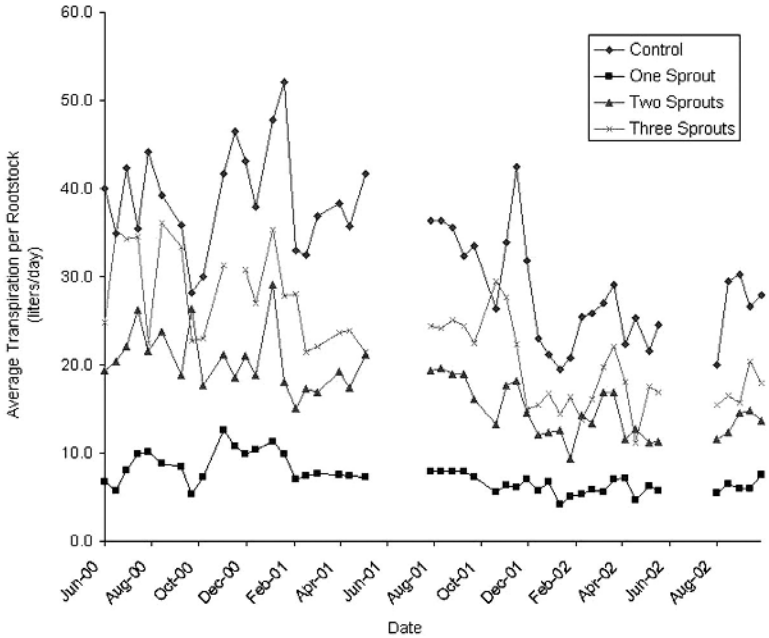
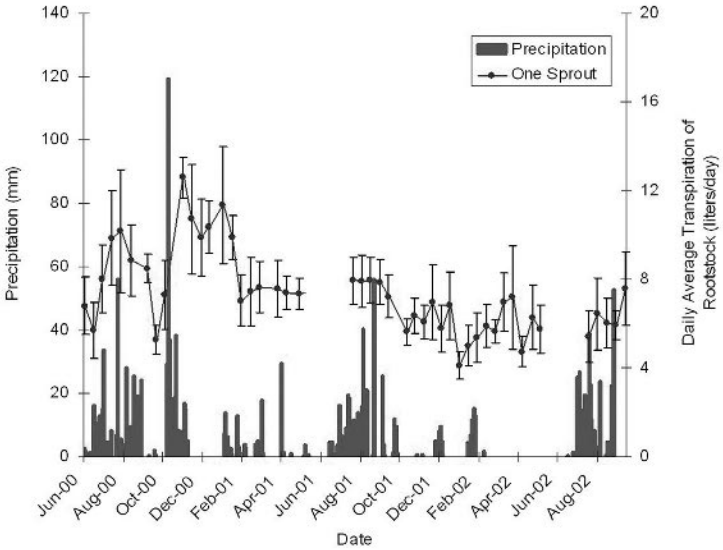


Figure 3—Average daily transpiration rates by rootstocks for three coppice thinning treatments and the unthinned control from June 2000 to September 2002.



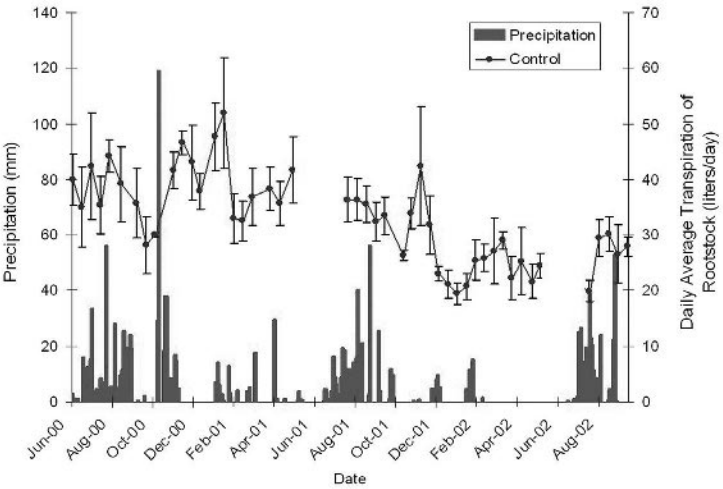


Figure 4—Seasonal trends in daily transpiration rates by rootstocks of Emory oak from June 2000 to September 2002 for (upper) coppice thinned to one residual stump-sprout and (lower) the control. Bars on the transpiration line represent standard errors.

procedures described in the earlier study of Emory oak transpiration rates (Ffolliott and others 2003).

Table 2 shows that thinning Emory oak coppice has a potential to increase the amount of water available to recharge groundwater aquifers, produce streamflow, or, depending on the soil moisture conditions, aid the growth of other plants in comparison to the amount of water available with unthinned postharvest rootstocks. The transpiration component of the hydrological cycle in Emory oak woodlands, therefore, can be altered through implementing coppice thinning treatments.

Multiple Use Management

Options for thinning the coppice in Emory oak stands that have been subjected to earlier harvesting of fuelwood can be oriented toward (1) minimizing onsite water losses to the transpiration process, (2) maximizing fuelwood production, (3) attaining the structural diversity necessary for wildlife habitats, or (4) combinations of these three options. Because of the increasing ecosystem-based, multiple-use orientation of managing Emory oak stands in the Southwestern United States (Ffolliott 1999, 2002, McClaran and McPherson 1999), the latter option is a common management goal. A decision matrix has been developed to assist managers in attaining this management goal. This decision matrix is based on proxies that have been derived from studies in the Emory oak woodlands of southeastern Arizona.

Proxies for Resources

Water loss through transpiration by thinned Emory oak coppice, which is likely the largest component of the water budget in the Emory oak woodlands (Ffolliott 2000), has been quantified in the current transpiration study and the study reported on earlier (Ffolliott and Gottfried 2000, Ffolliott and others 2003). Water that is lost to transpiration is not available to produce runoff, recharge groundwater aquifers, or grow plants. Therefore, knowledge of transpiration rates is a key to selecting a coppice thinning treatment that minimizes water loss on a site and, as a consequence, was selected as the proxy for water in formulating the decision matrix. On a daily basis, average transpiration rates for thinned Emory oak rootstocks ranged from lowest to highest in thinned clumps of one, two, and three sprouts, respectively. Unthinned rootstocks transpired the highest amount of water from a site.

Growth and volume of thinned Emory oak coppice are the proxy for wood in the decision matrix. When the management objective focuses largely on utilizing Emory oak coppice for fuelwood and a decision must be made to thin the coppice resulting from earlier harvesting activities, then thinning to retain one residual sprout is recommended (Bennett 1988, 1990, Touchan and Ffolliott 1999, Farah and others 2003). Growth and volume are concentrated in the single stem and, as a consequence, that stem will attain a desired volume for fuelwood in a shorter period. The next "best options" are thinning the coppice to two sprouts and then three sprouts. Growth and volume are comparatively minimal in the absence of thinning, and therefore, this is the least preferred of the management options.

Age of the coppice at the time of thinning also affects growth of the sprouts (Bennett 1988, 1990, Touchan and Ffolliott 1999, Farah and others 2003). Resprouting is likely if the sprouts are thinned too soon, reducing the effectiveness of the thinning treatment. When thinning is delayed too long, growth can be lost to competition and mortality.

The abundance of foliage in the vertical layers of the crowns is the proxy for wildlife habitats. When the management objective is to sustain the structural diversity of wildlife habitats, a decision not to thin Emory oak coppice is the most preferred management option considered in this paper (Sharman and Ffolliott 1992). Harvesting removes the taller trees that provide a greater number of habitat niches for nongame bird species (Balda 1969, Block and others 1992) and other wildlife than do shorter trees. Furthermore,

Table 2—Annual transpiration in stands of thinned Emory oak coppice and the percent of annual precipitation transpired by the coppice in 2001.

Transpiration	Thinning treatment			
	One sprout	Two sprouts	Three sprouts	Control
Daily transpiration (L)	7.48 ± 0.306	17.7 ± 0.860	23.7 ± 1.12	35.3 ± 1.72
Transpiration per unit area of coppice (mm/yr)	67.9	160	215	320
Total transpiration of coppice and mature trees* (mm/yr)	181	273	328	433
Annual Precipitation Transpired in 2001 (%)	33.5	50.5	60.7	80.2

*Estimated transpiration for mature Emory oak trees was 17.5 L/day (Folkerts 1999)

thinning of the coppice resulting from earlier harvesting activities eliminates much of the remaining structural diversity by removing many of the intermediate trees. Thinning, therefore, should not be prescribed so that a minimum level of biomass is retained in the harvested woodland. Ordering of the management options to sustain the structure diversity of Emory oak coppice from most preferred to least preferred is no thinning, thinning to three residual sprouts, thinning to two sprouts, and thinning to one sprout.

Incorporating the three proxies for water, wood, and wildlife into a simple decision matrix for selecting thinning options for stands of Emory oak coppice results in table 3. While other management options are likely, those displayed in this table were derived from research results and, therefore, are the basis for solving the decisionmaking problem illustrated below.

Decisionmaking Problem

Problems arise when the integration of resource management goals or objectives is complex and involves different management disciplines. Therefore, a manager can be faced with the decisionmaking task of obtaining a fair and equitable solution to the problems of integrated resource management. This decisionmaking task is generally viewed in terms of the sequential steps of problem recognition, specification of strategies, specification of decision criterion or criteria, and selection of the optimum management strategy. To illustrate the decisionmaking process to optimize management of the thinned Emory oak coppice for water, wood, and wildlife benefits, we assumed that the problem confronted is minimizing water loss on a site while optimizing fuelwood production and structural diversity of wildlife habitats. Strategies available for solving this problem are centered on thinning the coppice to one, two, or three of the dominant sprouts or not thinning at all but retaining the coppice as it evolves naturally following a fuelwood harvest. The decision criterion in this example is to optimize the water, wood, and wildlife benefits of a selected thinning practice. Methods available to solve this type of problem include the use of a simplistic approach or more rigorous approaches.

Table 3—A decision matrix for selecting thinning options for Emory oak coppice.

	Alternative thinning treatments			
Criteria	**One**	**Two**	**Three**	**No thinning**
Water	4	3	2	1
Wood	4	3	3	1
Wildlife	1	2	3	4

Ranking: 4 = most preferred, 1 = least preferred

The simplistic approach requires a knowledge of the "values" that stakeholders have placed on the resource benefits considered. There are two cases to consider in applying this approach. All of the resources of interest have equal benefit to stakeholders in the first case, while stakeholders have placed preferential (unequal) values on the resource benefits in the second case. As these latter values reflect the "collective biases" of the stakeholders, it is plausible that stakeholders representing "water interests" place higher values on water than on wood or wildlife, while stakeholders with "wood interests" place higher values on wood and stakeholders with "wildlife interests" place higher values on wildlife. The stakeholders with "decisionmaking advantages" would dominate when collective bargaining becomes necessary.

Problems confronted by resources managers more typically involve a number of management objectives. A set of such objectives will likely be subject to a number of linear and non-linear constraints. Problems of this form of decisionmaking must often be analyzed with models that are based on multiple criteria (objective) decision (MCDM) methods. MCDM techniques are designed to find the preferred solutions to problems where the discrete alternatives are evaluated against acceptance criteria (factors) ranging from quantitative (costs) to qualitative (desirability). Descriptions of these and other decisionmaking techniques, requirements for their use, and examples of their applications in natural resources management are found in Yakowitz and Hipel (1997), El-Swaify and Yakowitz (1998), Anderson and others (2000), de Steiguer and others (2003), and others. However, the decisionmaking problem presented in this paper can be considered within the framework of the more simplistic approach.

Solution to Problem

The decision outcome for the problem presented is based on the assumption that all benefits are weighed equally. When the management objective is to minimize water losses to transpiration and optimize fuelwood production and structural diversity of wildlife habitats, then thinning Emory oak coppice evolving from earlier fuelwood harvesting to one residual sprout is the best compromise (table 3). Water losses to the transpiration process are minimized, and the growth and yield of the residual sprout are maximized by thinning the rootstocks to one residual sprout. Unfortunately, the structural diversity of wildlife habitats is reduced by this thinning treatment relative to the other options. While changes in structural diversity inevitably result from harvesting fuelwood and imposing subsequent coppice thinning treatments, a need for nongame bird habitat niches might still be met at "an acceptable level" with this thinning prescription.

Conclusions

Knowledge of how transpiration and other hydrological and ecosystem processes are affected by thinning Emory oak coppice is necessary to implement a thinning treatment that meets predetermined objectives. Therefore, the information presented in this paper should help contribute to the multiple use management of Emory oak woodlands of the Southwestern United States. The decision matrix presented in this paper should be useful to managers planning to enhance water, wood, and wildlife benefits of these woodlands. However, incorporating other resources (forage for livestock, settings for recreational opportunities, and so forth) into the decision matrix is necessary before truly holistic and ecosystem-based stewardship of these fragile ecosystems becomes possible.

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