AN ECOSYSTEM APPROACH TO DETERMINING EFFECTS OF PRESCRIBED FIRE ON SOUTHWESTERN BORDERLANDS OAK SAVANNAS: A BASELINE STUDY

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ABSTRACT

Many traditional land management activities and supporting research have concentrated on one or two resources, with limited evaluations of interactions among other potential values. An ecosystem approach to land management requires an evaluation of the blend of physical and biological factors needed to assure productive, healthy ecosystems. Ideally, social and economic values also should be considered. The U.S. Department of Agriculture Forest Service's Coronado National Forest and its partners have just completed a draft for the Peloncillo Programmatic Fire Plan to address fire management strategies for this mountain range, which lies along the southern Arizona–New Mexico border. The plan was designed to reintroduce prescribed or managed fires into an area where wildfires have been excluded since the late 19th century. One persistent question concerned the impacts of cool-season (November–April) and warm-season (May–October) fires on the oak (*Quercus* spp.) ecosystems that are common throughout these mountains. Fires normally occur in June or early July before the summer monsoon rains. However, hotter warm-season fires could damage important wildlife habitats by killing larger numbers of standing trees and shrubs used as nesting sites or cover or as sources of food, and thus some managers prefer burning during the cooler season.

The Rocky Mountain Research Station's Southwestern Borderlands Ecosystem Management Project and its cooperators have initiated a research program to evaluate the impacts of season of burning on a large number of ecosystem components, including hydrology, sedimentation, vegetation, soil nutrient dynamics, small and large mammals, birds, and snakes and other reptiles. Our research is concentrated on 12 small, gauged watersheds that support oak savannas or open woodlands. We plan to burn four watersheds in the warm season, burn four in the cool season, and leave four as controls. The watershed and companion studies are currently in the pre-burn calibration phase. However, little is actually known about the oak ecosystems of the southwestern United States and northern Mexico, where most of these oak stands are found. The preliminary results have provided important new information about these lands. This paper describes the studies and initial results obtained during the pre-treatment phase of this project.

keywords: ecosystem approach, oak (*Quercus*) savannas, prescribed fire, seasonal burning, southwestern Borderlands.

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INTRODUCTION

Fire, which normally occurred as the result of lightning during the late spring and early summer, was the most important natural disturbance in the oak (*Quercus* spp.) woodlands and savannas of the southwestern United States and northern Mexico prior to European–American settlement. Some fires were set by Chiricahua Apaches, but the impacts probably were limited (Kaib et al. 1999). However, more than a century of settlement has altered the dynamics in these ecosystems, resulting in declines in native herbaceous species, less frequent fires, and increases in woody species. The loss of a continuous herbaceous cover limited the spread of natural fires and allowed seedlings of woody species to become established. Prescribed fire is seen as a technique for restoring the natural processes within the savannas.

The U.S. Department of Agriculture (USDA) Forest Service's Coronado National Forest and its partners have just completed a draft for the Peloncillo Programmatic Fire Plan to address fire management strategies for the Peloncillo Mountain range, which lies along the southern Arizona–New Mexico border. One persistent question concerned the impacts of cool-season (November–April) and warm-season (May–October) prescribed fires on the oak ecosystems that are common throughout these mountains. Fires normally occur in June or early July before the summer monsoon rains. However, there are questions about the effects

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of different burning seasons and fire intensities on this ecosystem. Many managers would like to duplicate natural warm-season burning, but others prefer low-severity, cool-season burning in the early spring or winter. Severe warm-season fires could destroy vegetation and litter, result in soil water repellency, and impact important wildlife habitats. Hotter warm-season fires could damage important wildlife habitats by killing larger numbers of standing trees and shrubs used as nesting sites, thermal or hiding cover, or species such as Palmer agave (*Agave palmeri*) that provide nectar for endangered lesser long-nosed bats (*Leptonycteris curasoae*) (Slauson et al. 1999). The potential conversion of large areas of woodlands or savannas to open grasslands would affect the habitat of the threatened New Mexico ridge-nosed rattlesnake (*Crotalus willardi obscurus*), and fire potentially could cause snake mortality (Holycross et al. 1999). Cool-season fires, however, could leave the soil surface without a protective cover for a longer period, resulting in increased erosion because most native herbaceous species grow and germinate during the summer monsoon period.

The USDA Forest Service's Rocky Mountain Research Station's Southwestern Borderlands Ecosystem Management Project and its cooperators have initiated a research program to evaluate the impact of season of burning using an ecosystem approach in which a large number of ecosystem components, including hydrology, sedimentation, vegetation, soil nutrient dynamics, small and large mammals, birds, and snakes and other reptiles are evaluated. An ecosystem approach to land management requires an evaluation of the blend of physical and biological factors needed to assure productive, healthy ecosystems (Kaufmann et al. 1994). Ideally, social and economic values also should be considered.

Encinal or oak woodlands and savannas together cover >80,000 km^2 in the United States and Mexico. Much is known about the oak woodlands but less about oak savannas. Ecological, hydrological, and environmental characterizations of the woodlands have been obtained through collaborative efforts involving a large number of people (McPherson 1992, 1997; DeBano et al. 1995; Ffolliott 1999, 2002; McClaran and McPherson 1999). Comparable characterizations of the lower-elevation oak savannas and open woodlands are needed to enhance the knowledge of all of the oak ecosystems in the Madrean Archipelago region. Oak savannas differ from oak woodlands in that their structure is more open with fewer trees and, as a consequence, a higher level of herbaceous production might be expected. We describe studies and preliminary results obtained during the pre-treatment phase of the project and provide information on hydrologic and erosion–sedimentation characteristics, tree overstory species composition and density, herbaceous understory production, and observations of indigenous wildlife species.

STUDY AREA

Twelve small watersheds were selected in the oak savannas on the eastern side of the Peloncillo Mountains of southwestern New Mexico to evaluate the impacts of cool- and warm-season prescribed burning treatments on the hydrological and ecological characteristics of the watersheds (Gottfried et al. 2000) and collectively form the study area (Figure 1). These watersheds, called the Cascabel watersheds, cover a total area of 182.6 ha. Individual watersheds range in area from approximately 24.0 ha (Watershed E) to 7.6 ha (Watershed G). The area is typical of oak savannas and open woodlands of the region. The Cascabel Watershed study area (lat 31°33′N, long 108°59′W) is largely within the Douglas Ranger District of the Coronado National Forest and adjacent to the Diamond A Ranch in New Mexico. The watersheds are situated between 1,640 and 1,705 m in elevation, and the nearest long-term precipitation station indicates that annual precipitation averages 597 mm, with nearly one-half occurring during the summer. Geological, physiological, and vegetation characteristics of the Cascabel watersheds have been previously described by Gottfried et al. (2000, 2002) and Neary and Gottfried (2004).

EXPERIMENTAL DESIGN AND SAMPLING METHODS

Physical Components

Hydrology

The six watersheds on each side of the ridge were divided into two groups of three (Figure 1). Each set will have the two burning treatments and an untreated control treatment that will be assigned randomly. The effects of treatments will be assessed by comparing the changes between pre- and post-treatment observations on the treated watersheds to comparable observations on the untreated watersheds. Streamflow data from individual storms will be the primary parameter in the analysis of treatment effects. The watersheds currently are being calibrated and treatments will be initiated once sufficient data are collected to describe pre-treatment conditions. The current 6-y drought has prolonged the calibration period.

Each watershed contains two Parshall flumes: a small flume with the capacity of 122 L/s to measure common low flows and a larger flume to measure anticipated large flows. Eight of the larger flumes have a capacity of 1,628 L/s and four have a capacity of 1,209 L/s (Gottfried et al. 2000). A sediment dam was constructed in each watershed, and permanent channel cross-section stations have been established and measured. Two complete weather stations and six supplemental recording precipitation gauges have been established throughout the watershed area.

Erosion and Sedimentation—Channel Characteristics

An early decision was to determine the character of all the channels in the 12 Cascabel watersheds because of the observed differences in channel conditions and the wide range of values in peak discharges that were estimated by using field measurements and U.S. Geological Survey and Natural Resources Con-

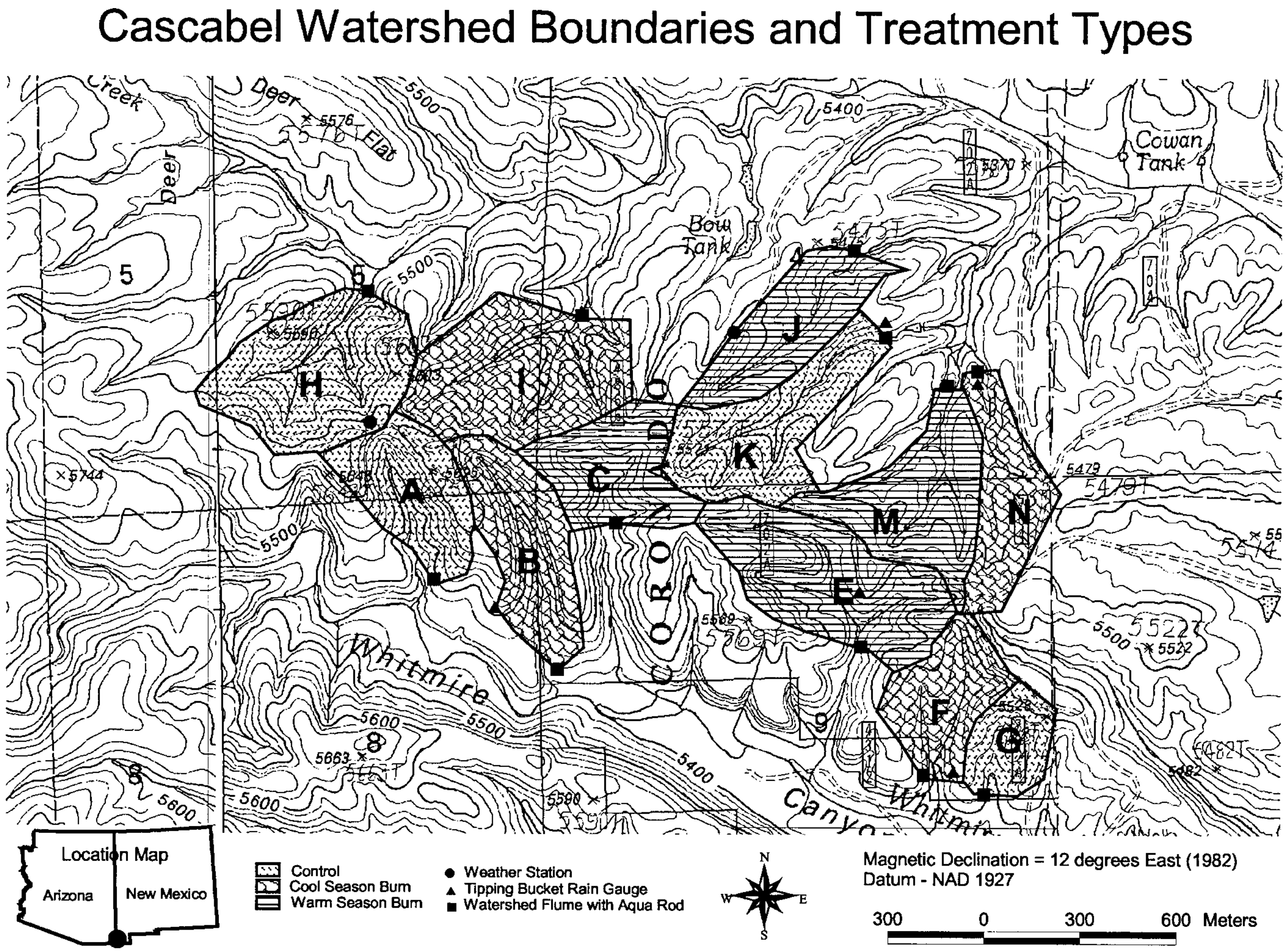

Fig. 1. The 12 Cascabel watersheds, Peloncillo Mountains, southwestern New Mexico, were divided into four groups of three watersheds and the potential burning season and control treatments were randomly assigned. Watersheds A, G, H, and K have been designated as controls, watersheds B, F, I, and N will receive warm-season burns, and watersheds C, E, J, and M will receive cool-season burns. Another analysis following the pre-treatment period may require that some treatments be reassigned among watersheds.

servation Service methods (Gottfried et al. 2000). A consensus opinion was reached among the principal investigators that the physical condition of the channels might strongly influence hydrologic responses, especially where long reaches of channel consisted mainly of bedrock outcrops.

Line-transect surveys were conducted on all channels, including side channels, starting at the larger Parshall flume and continuing upslope along the channel until the channel was no longer discernable. Lengths of channel were classified as bedrock, coarse alluvium, fine alluvium (sand), vegetation, woody debris, and other. Accumulated lengths of each class were summed for each watershed.

Side-Slope Erosion

Three erosion pins were installed in May 2004 around every third sample point used for vegetation and wildlife studies on each of the watersheds. These formed the basis to estimate soil erosion. Two erosion pins were placed about 1.8 m upslope and one erosion pin was placed 1.8 m downslope of the points. A total of 438 erosion pins was installed on the study area. Initial measurements of soil loss were made in October 2004 following the summer monsoon rains of the year. The erosion pins were reset after this measurement to facilitate estimates of future soil loss. A bulk density value obtained from soil samples collected on the watersheds was used as the basis to convert measurements of average soil loss on a watershed to corresponding erosion rates in terms of metric tons per hectare.

Biological Ecosystem Components

Vegetation

On each of the 12 Cascabel watersheds, between 35 and 45 sample points were located along transects perpendicular to the main stream system and extended from ridge to ridge. Intervals between the sample plots varied among the watersheds depending on the size and configuration of the watershed sampled. A total of 421 sample points were located on the watersheds. Measurements of tree overstory conditions and estimates of herbaceous production were obtained on plots centered over these sample points. Species composition and density of the tree overstory were measured on 0.10-ha circular plots. Single-stemmed trees were measured in terms of their diameter root collar (DRC) and multiple-stemmed trees in equivalent diameter root collar, following procedures outlined by Chojnacky (1988). Tree density is expressed in stems per hectare. Dead and down woody material was measured at the points using the survey technique developed by Brown (1974). Production (standing biomass) of grasses, forbs, and shrubs in the understory was estimated using 0.89-m^2 plots. These components of herbage production were estimated by weight-estimate procedures (Pechanec and Pickford 1937) in the spring (early growers) and fall (late growers).

Wildlife

Accumulations of fecal droppings (pellets) were tallied and then cleared on 0.004-ha plots centered over sample points in the spring (late May) and fall (early October) to assess the occurrence of white-tailed deer (*Odocoileus virginianus*), mule deer (*O. hemionus*), and desert cottontail (*Sylvilagus audubonii*). Bird sightings in a 5-min observation period were tallied by species at the sample points to characterize avifauna on the study area during a week in late May and a week in early October.

RESULTS AND DISCUSSION

Physical Components

Hydrology

Hydrological measurements were started in 2001; unfortunately, the continuing regional drought has limited the number of streamflow events during the past 4 y. A total of 21 events have been measured but only two, occurring in January 2005, were measured on all 12 watersheds. The January storms, which produced about 73.7 mm of precipitation, produced peaks on all watersheds, with a range of 45.3 L/s on Watershed H to 184.0 L/s on Watershed I. Peak flows of between 96.3 and 150.1 L/s were recorded on several watersheds during a summer rainstorm on 31 August 2004. Additional peak flow events from the summer of 2005 currently are being evaluated.

Channel Characteristics

Channel distances ranged from 420 m for Watershed A (Figure 1) to 1,763 m for Watershed E, which has two main forks; the mean distance for the 12 watersheds is 1,020 m (Neary and Gottfried 2004). There appears to be a great disparity in percentage of individual watershed channel characteristics (Figure 2), although differences have not been evaluated statistically. Rock-lined areas occur within 6.4% of the channel in Watershed A and 41.0% in Watershed K. There was also a large range between all the Cascabel watersheds in fine alluvium (0.2–35.7%) and coarse alluvium (18.3–74.0%). Coarse alluvium channel material is the most common characteristic dominating all watershed channels except watersheds K and N. The type of channel substrate could make a significant difference in total water yields as well as storm peak flow responses. The watersheds with the higher percentages of bedrock channels are apt to be ‘‘more flashy’’ in nature, producing peak flows more rapidly than watersheds with less rock. The watersheds with the higher percentages of alluvium in their channels might prove to be less flashy and have lower but sustained flows because their channels would have a larger in-channel water storage capacity. There was far less variation among watersheds in the remaining three categories (vegetation, woody debris, and other), which have been combined in Figure 2. Channels on watersheds F and G had the greatest amounts of vegetation and woody debris.

Side-Slope Erosion

The first known estimates of surface erosion on a watershed basis in the oak savannas of the southwestern United States have been obtained on the Cascabel watersheds. Two measurements of soil erosion are currently available, one following the summer monsoon season of 2004 and the second in the spring of 2005 after the winter precipitation period. Estimated soil erosion averaged 23.8 t/ha on the 12 Cascabel watersheds (collectively) following the summer monsoons, with estimates on individual watersheds ranging from 10.8 to 38.3 t/ha. Soil erosion after the winter precipitation period, which included several high-intensity precipitation events, was estimated to be 27.1 t/ha, ranging from a low of 7.8 to a high of 40.6 t/ha. For the year of measurement, therefore, the soil erosion rate was 50.9 t/ha. No meaningful relationships between the magnitude of the estimated soil erosion on the individual Cascabel watersheds and the corresponding watershed size, stream-channel network, and physiography (slope position, slope percent, aspect) were evident in this initial analysis. A longer period of measurement is needed to detect these relationships if they exist.

Biological Ecosystem Components

Tree Overstories

The dominant species tallied on the Cascabel watersheds were Emory (*Quercus emoryi*) (60.1% of all trees tallied), Arizona white (*Q. arizonica*; 11.9%), and Toumey (*Q. toumeyi*; 4.4%) oaks and alligator juniper (*Juniperus deppeana*; 15.3%). Minor components are redberry juniper (*J. coahuilensis*; 2.0%), pinyon (*Pinus discolor*; 5.6%), and mesquite (*Prosopis glandulosa*; 0.7%).

Tree densities on the study area were summarized by total number and volume of all trees in size-class categories listed by O’Brien (2002) for the woodland types of the southwestern United States: saplings (2.5–12.4 cm DRC), medium trees (12.7–22.6 cm DRC), and large trees (22.9 cm DRC and larger). There were

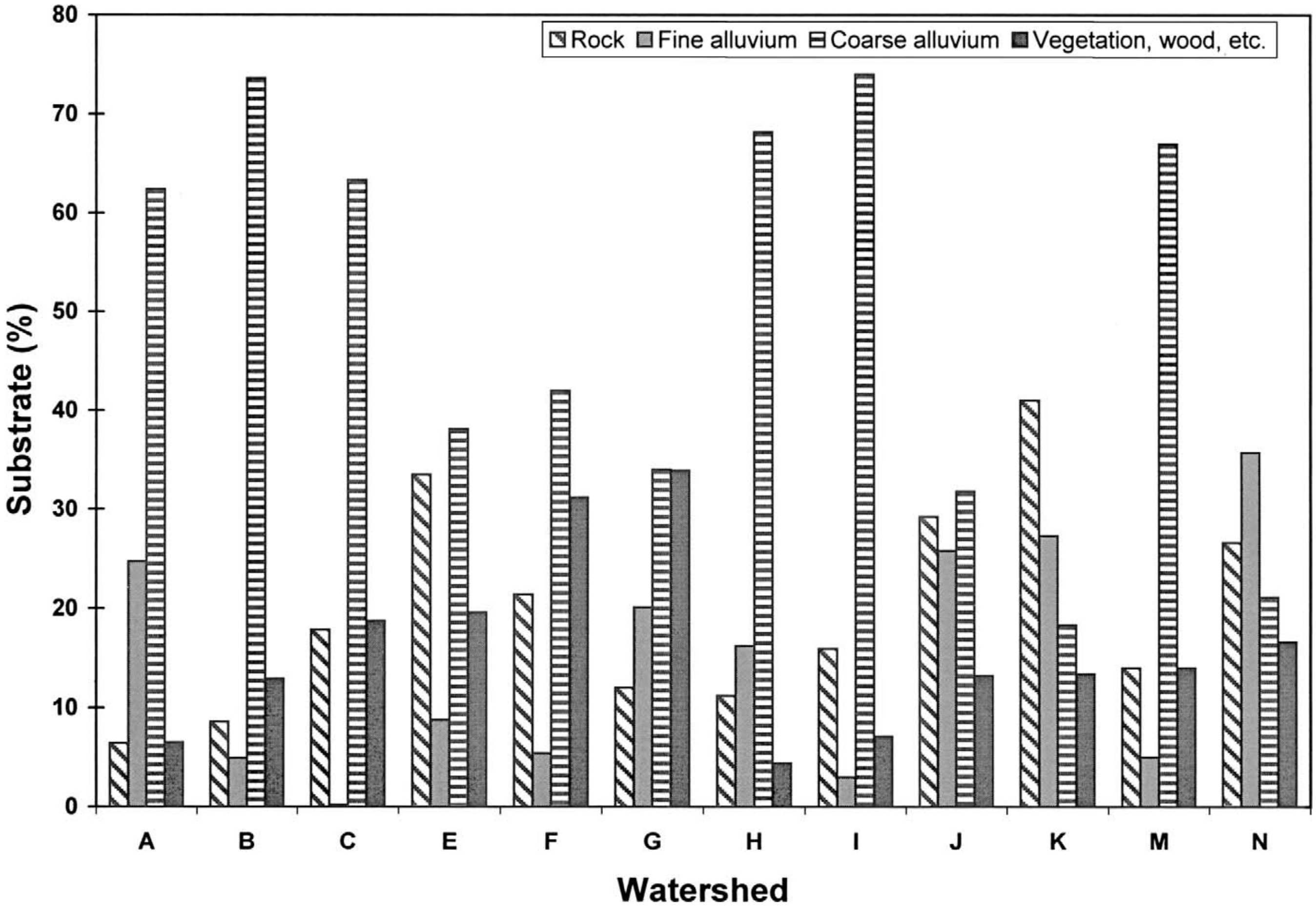

Fig. 2. Channel substrate characteristics of the 12 Cascabel watersheds, Peloncillo Mountains, southwestern New Mexico. These data are adapted from Neary and Gottfried (2004).

130.0 trees and 0.10 m^3 of volume per hectare in saplings, 45.5 trees and 0.89 m^3 of volume per hectare in medium trees, and 47.2 trees and 10.17 m^3 of volume per hectare in large trees. Total densities were 222.7 trees and 11.16 m^3 of volume per hectare. Approximately 58% of the trees were in the sapling class and the rest of the trees were almost equally divided between the two larger classes. These densities were generally less than observed in the higher-elevation oak woodlands that receive higher amounts of annual precipitation and support more than twice as many trees per hectare (Ffolliott and Gottfried 2005).

Dead and Down Woody Fuels

The average dead and down woody fuels on all watersheds combined was 1.61 t/ha. Nearly 90% of the material was Emory oak twigs and small branches. Most of the material was $<$1.2 cm in diameter and $<$0.6 m in length.

Herbaceous Understories

Included among the more commonly encountered grasses on the Cascabel watersheds were blue (*Bouteloua gracilis*), sideoats (*B. curtipendula*), slender (*B. repens*), and hairy (*B. hirsuta*) grama, bullgrass (*Muhlenbergia emersleyi*), common wolfstail (*Lycurus phleoides*), and Texas bluestem (*Schizachyrium cirratum*). Forb species, including species of verbena (*Verbena* spp.) and mariposa lily (*Calochortus* spp.), are comparatively minor herbaceous components. Buckbrush (*Ceanothus* spp.), beargrass or sacahuista (*Nolina microcarpa*), fairyduster (*Calliandra eriophylla*), and common sotol (*Dasylirion wheeleri*) are scattered shrubs and half-shrubs on the area.

Total production of grasses, forbs, and shrubs on the Cascabel watersheds in the spring and fall of 2003 was 260.8 and 218.3 kg/ha, respectively. The corresponding levels of herbage production in 2004 were 198.5 and 202.3 kg/ha, respectively. We assumed that observed herbage production estimates reflect the influence of prolonged drought in the region. Estimates of herbage production continue to be made to adequately reflect variability in precipitation amounts and distribution on the study area.

The predominantly oak overstories in the savannas on the watersheds do not appear to affect herbage production. This observation is contrary to the commonly reported relationship of increasing herbaceous cover with decreasing overstory density (Ffolliott and Clary 1982). The lack of similar overstory–understory relationships has been reported for other southwestern oak ecosystems (Ffolliott and Gottfried 2005). However, the reverse situation might not be true. McClaran and McPherson (1999) reported that a dense cover of perennial grass can limit successful Emory oak regeneration on ungrazed sites in similar oak ecosystems. Further study is necessary to verify the overstory–understory relationships or to identify other important variables, such as crown characteristics, that may influence herbaceous production.

Utilization of the herbaceous plants by herbivores has averaged $<5\%$ in both years of study. However, cattle had been removed from the Cascabel watersheds and the surrounding areas by local ranchers for several months in the summer and early fall of 2004 because of the prolonged period of below-average annual precipitation. Populations of indigenous herbivores have also been low on the watersheds in recent years.

Wildlife

Abundance and habitat preferences of birds and some of the other wildlife found in the densely structured oak woodlands of the southwestern United States are known for some of the representative species, but little information on these topics is available for the more open oak savannas of the region. White-tailed deer on the Cascabel watersheds are largely scattered throughout the year. However, population estimates are unreliable because of the limited time that pellet counts have been tallied. Patterns of repeated observations of pellet accumulations and habitat conditions (vegetation, physiography, etc.) at the sample points were inconclusive. Findings and conclusions for desert cottontail were similar. A larger number of birds and a greater diversity of species were observed on the Cascabel watersheds in the spring (May) than in the fall (October) (Jones et al. 2005). While some species, such as bushtit (*Psaltriparus minimus*), Mexican jay (*Aphelocoma ultramarina*), juniper titmouse (*Baeolophus ridgwayi*), mourning dove (*Zenaida macroura*), and scaled quail (*Callipepla squamata*), were tallied in both observation periods, other species such as dusky-capped flycatcher (*Myiarchus tuberculifer*), northern mockingbird (*Mimus polyglottos*), and turkey vulture (*Cathartes aura*) were observed in spring but not in fall. Montezuma quail (*Cyrtonyx montezumae*) were observed only in the fall. It remains to be seen if this pattern of abundance and species diversity continues to persist on the watersheds in the future. No meaningful relationships between bird sightings and the habitat conditions represented by the sample points were observed.

CONCLUSIONS

Researchers and land managers are attempting to learn more about the oak ecosystems of the southwestern United States and northern Mexico so that sound land stewardship can be maintained or enhanced. Learning of the impacts of the planned reintroductions of fire into these ecosystems is a primary component in these efforts. Studies on the hydrology and erosion–sedimentation dynamics and the related biological impacts of prescribed fire treatments in the oak savannas in the southwestern Borderlands is a focus of this research project. We described initial results of the pre-treatment phase of the study. Experimental designs and sampling methods were selected to be able to detect statistical differences in the measured ecosystem characteristics between the pre-treatment and post-treatment conditions. The calibration period will be monitored until a sufficient number of storm events is observed to provide estimated statistical power of 0.90 to detect hydrologic changes of 100% with a significance of 0.05. Analyses of the biological resources responses assume a level of significance between 0.15 and 0.20.

Detectable changes can only be surmised at this time. Nevertheless, we anticipate post-treatment changes in the timing of streamflow and discharge rates. Side-slope erosion rates are likely to increase, leading to changes in channel conditions. Species compositions might change and the production of grasses, forbs, and shrubs will likely increase after the prescribed fire treatments as a result of the decrease in tree overstory densities and removal of litter and duff layers. Increased browse should be available to deer populations because the oak species on the watersheds readily sprout following fire. Ground-nesting avifauna is anticipated to decrease in numbers and diversity, while avifauna nesting in standing dead trees (snags) should increase. Reducing the loadings of dead and down woody material and other fuel fractions, one of the main objectives of the prescribed fire treatments, should occur. All of these possible changes will be evaluated and contrasted within the context of the planned cool-season and warm-season fires.

Detection of these changes, if they occur, will be determined in two ways. If post-treatment weather regimes are similar to those encountered in the pre-treatment phase—the latter representing a drought condition—comparisons of before and after ecosystem characteristics should provide the necessary information. However, if the two weather regimes are significantly different, comparison will be made between changes on burned and unburned control watersheds. Both approaches are planned in an effort to provide the most comprehensive picture of the effects of prescribed fire in the oak savannas.

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LITERATURE CITED

Brown, J.K. 1974. Handbook for inventorying downed woody material. General Technical Report INT-16, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Chojnacky, D.C. 1988. Juniper, pinyon, oak, and mesquite volume equations for Arizona. Research Paper INT-391, U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT.

DeBano, L.F., P.F. Ffolliott, G.J. Gottfried, R.H. Hamre, and C.B. Edminster (technical coordinators). 1995. Biodiversity and management of the Madrean Archipelago: the sky islands of southwestern United States and northern Mexico. General Technical Report RM-264, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Ffolliott, P.F. 1999. Encinal woodlands in the southwestern United States. Pages 69–81 *in* P.F. Ffolliott and A. Ortega-Rubio (eds.). Ecology and management of forests, woodlands, and shrublands in the dryland regions of the United States and Mexico: perspectives for the 21st century. Centro de Investigaciones Biológicas del Noroeste, La Paz, Mexico.

Ffolliott, P.F. 2002. Ecology and management of evergreen oak woodlands in Arizona and New Mexico. Pages 304–316 *in* W.J. McShea and W.M. Healy (eds.). Oak forest ecosystems: ecology and management for wildlife. Johns Hopkins University Press, Baltimore, MD.

Ffolliott, P.F., and W.P. Clary. 1982. Understory–overstory vegetation relationships: an annotated bibliography. General Technical Report INT-136, U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT.

Ffolliott, P.F., and G.J. Gottfried. 2005. Vegetation characteristics of oak savannas in the southwestern United States: a comparative analysis with oak woodlands in the region. Pages 399–402 *in* G.J. Gottfried, B.S. Gebow, L.G. Eskew, and C.B. Edminster (compilers). Connecting mountain islands and desert seas: biodiversity and management of the Madrean Archipelago. Proceedings RMRS-P-36, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Gottfried, G.J., D.G. Neary, and R.J. Bemis. 2000. Watershed characteristics of oak savannas in the southwestern borderlands. Hydrology and Water Resources in Arizona and the Southwest 30:21–28.

Gottfried, G.J., D.G. Neary, and R.J. Bemis. 2002. Assessing the impacts of prescribed burning on soil and water resources of oak savannas in the southwestern United States. Pages 115–122 *in* Assessing capabilities of soil and water resources in drylands: the role of information retrieval and dissemination technologies. International Arid Lands Consortium, 20–25 Oct 2002, Tucson, AZ.

Holycross, A.T., L.J. Smith, C.W. Painter, and M.E. Douglas. 1999. Effects of prescribed fire on montane rattlesnakes: endangered species and ecosystem restoration. Pages 109–110 *in* G.J. Gottfried, L.G. Eskew, C.G. Curtin, and C.B. Edminster (compilers). Toward integrated research, land management, and ecosystem protection in the Malpai Borderlands: conference summary. Proceedings RMRS-P-10, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Jones, W.D., C.M. Jones, P.F. Ffolliott, and G.J. Gottfried. 2005. Abundance of birds in the oak savannas of the southwestern United States. Pages 523–524 *in* G.J. Gottfried, B.S. Gebow, L.G. Eskew, and C.B. Edminster (compilers). Connecting mountain islands and desert seas: biodiversity and management of the Madrean Archipelago. Proceedings RMRS-P-36, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Kaib, M., T.W. Swetnam, and C.H. Baisan. 1999. Fire history in canyon pine–oak forests, intervening desert grasslands, and higher-elevation mixed-conifer forests of the Southwest Borderlands. Pages 57–64 *in* G.J. Gottfried, L.G. Eskew, C.G. Curtin, and C.B. Edminster (compilers). Toward integrated research, land management, and ecosystem protection in the Malpai Borderlands: conference summary. Proceedings RMRS-P-10, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Kaufmann, M.R., R.T. Graham, D.A. Boyce Jr., W.H. Moir, L. Perry, R.T. Reynolds, P. Mehlhop, C.B. Edminster, W.M. Block, and P.S. Corn. 1994. An ecological basis for ecosystem management. General Technical Report RM-246, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

McClaran, M.P., and G.R. McPherson. 1999. Oak savanna in the American Southwest. Pages 275–287 *in* R.C. Anderson, J.S. Fralish, and J.M. Baskin (eds.). Savannas, barrens, and rock outcrop plant communities of North America. Cambridge University Press, New York.

McPherson, G.R. 1992. Ecology of oak woodlands in Arizona. Pages 24–33 *in* P.F. Ffolliott, G.J. Gottfried, D.A. Bennett, V.M. Hernandez C., A. Ortega-Rubio, and R.H. Hamre (technical coordinators). Ecology and management of oak and associated woodlands. General Technical Report RM-218, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

McPherson, G.R. 1997. Ecology and management of North American savannas. University of Arizona Press, Tucson.

Neary, D.G., and G.J. Gottfried. 2004. Geomorphology of small watersheds in an oak encinal in the Peloncillo Mountains. Hydrology and Water Resources in Arizona and the Southwest 34:65–71.

O'Brien, R.A. 2002. Arizona's forest resources, 1999. Resource Bulletin RMRS-RB-2, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT.

Pechanec, J.F., and G.D. Pickford. 1937. A weight estimate method for determination of range or pasture production. Journal of the American Society of Agronomy 29:894–904.

Slauson, L., V. Dalton, and D. Dalton. 1999. Effects of prescribed burning on the Palmer agave and lesser long-nosed bat. Pages 111–114 *in* G.J. Gottfried, L.G. Eskew, C.G. Curtin, and C.B. Edminster (compilers). Toward integrated research, land management, and ecosystem protection in the Malpai Borderlands: conference summary. Proceedings RMRS-P-10, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.