Fire Effects On the Soils and Hydrology of the Cascabel Watersheds in the Coronado National Forest, Madrean Archipeligo

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ABSTRACT--*Effects of cool-season (November-April) and warm-season (May-October) prescribed burning treatments and a spring wildfire on the soils and hydrologic functioning of the oak savannas on the Cascabel Watersheds in the Southwestern Borderlands Region of Arizona and New Mexico are reported in this paper. The impacts of the fire events on transpiration, formation of water repellent soils, hillslope soil erosion and deposition, streamflow regimes, and sediment depositions are among these soil and hydrologic functions. Results should be useful in planning management activities in similar oak savannas within Southwestern Borderlands Region.*

Keywords: fire effects, hydrologic functioning, oak savannas, prescribed burning, southwestern United States, Arizona, New Mexico

INTRODUCTION

Information on edaphicl characteristics and hydrologic functioning of the oak savannas in the Southwestern Borderlands Region had been limited until establishment of the Cascabel Watersheds on the eastern side of the Peloncillo Mountains in western New Mexico by the Rocky Mountain Research Station of the U.S. Forest Service. Oak savannas and woodlands cover several million acres of arid and semi-arid lands in the American Southwest and northern Mexico and are representative of dryland forests and savannas throughout the world (McPherson 1997). The Coronado National Forest in southern Arizona supports more than 761,000 ac of oak savannas and woodlands and the Tonto National Forest supports 94,000 . Oak savannas are situated in the transition between the higher-elevation oak woodlands and the lower-elevation desert grasslands and shrub communities in the region. While Niering and Lowe (1984), working in the Santa Catalina Mountains near Tucson, Arizona, described this band of vegetation as "open woodlands," the term "oak savannas" is preferred to differentiate this ecosystem from the more extensive oak woodlands. Oak savannas are more open in stand structure than the oak woodlands, and, therefore, a higher level of herbage production can occur (Ffolliott and Gottfried 2005, 2010, Ffolliott et al. 2008b).

Fire was a natural occurrence in oak ecosystems in the region before Euro-American settlement. However, natural fire frequencies, burning characteristics, and impacts on ecological characteristics and hydrologic functioning have been altered since the late 1800's because of two main factors. Past livestock grazing practices removed significant portions of the fire-carrying herbaceous vegetation and past aggressive fire suppression policies of management agencies reduced the number and aerial extent of many of the burning events. These past practices and policies have resulted in unnaturally high tree densities on many sites with the trees more susceptible to insects, diseases, and stand-replacing wildfire. A decline in production of herbaceous plants in the understories, often excessive loadings of flammable fuels, and invasion of mesquite (*Prosopis glandulosa*) and other woody plants onto productive grasslands added to the problem. As a consequence of these undesirable conditions, management agencies with support from their collaborators, including local staked holders and private organizations, became interested in re-introducing more natural fire regimes into the region's ecosystems including the oak savannas. However, more information on the impacts of burning on the ecological characteristics, soil conditions, and hydrologic functioning in the ecosystems was needed before such a program could be initiated. There were concerns how burning in the cool-season (November-April) or warm-season (May-October) would affect the ecology and hydrology of the savanna ecosystem, particularly the impacts of burning season on two listed species-the threatened New Mexico ridge-nosed rattlesnake (*Crotalus willardi obscurus*) and the Arizona listed Palmer's agave (*Agave palmeri*), which is important to the endangered lesser long-nosed bat

(*Leptonyceris curasoae*). Obtaining the necessary information was the primary reason for the establishment of the Cascabel Watersheds in a representative oak savanna (Edminster and Gottfried 1999, Gottfried and Edminster 2005, Gottfried et al. 2000, 2005). This paper reports on some of the soil and hydrology impacts.

CASCABEL WATERSHEDS

The Cascabel Watersheds were instrumented by the Rocky Mountain Research Station of the U.S. Forest Service in 2001 to study the effects of prescribed burning treatment on the ecological characteristics and hydrologic functioning of the watersheds. These watersheds are representative of the oak savannas found in the Malpai Borderlands and in the adjacent mountains of Arizona, New Mexico, and northern Sonora, Mexico. The Mapai Borderlands are situated within the larger Southwestern Borderlands Region as shown in Figure 1.

Characteristics

There are contain twelve watersheds in the Cascabel Watershed Study ranging from about 20 ac to almost 60 ac. They are situated 5,380 to 5,590 ft in elevation. Physiographic features of these watersheds are summarized in Table 1. Long-term annual precipitation measurements at the nearby Cascabel Ranch have averaged 21.8 in. However, a prolonged drought impacted the Southwestern Borderlands from the middle of the 1990s through the end of the study when the data and interpretations presented in this paper were collected. Annual precipitation in this drought has averaged 14.9 in. Bedrock geology of the watersheds is Tertiary rhyolite overlain by Oligocene-Miocene conglomerates and sandstone. Soils are classified as Lithic Argustolls, Lithic Haplustrolls, or Lithic Ustorthents. The depths of these soils are generally less than 20 in to bedrock. Mostly intermittent streamflow events originate on the watersheds with occasional large flows generated by high-intensity summer rains. Nearly 60 percent of the annual streamflow volume results from winter rains while the highest peak streamflows are generated by high-intensity rainstorms in the summer.

Dominant tree species are Emory (*Quercus emoryi*), Arizona white (*Q. arizonica*), and Toumey (*Q. toumeyi*) oak and alligator juniper (*Juniperus deppeana*). Minor components of the overstory are red berry juniper (*J. coahuilensis*), border pinyon (*Pinus bicolor*), and the tree-form of mesquite. (The term "tree overstories" refers to these species regardless of their size or position in the canopy.) The composition of tree species in the overstory is representative of the oak savannas in the region (Figure 2). The average acre at Cascabel contains 35 trees of all species and size classes (Ffolliott et al. 2008b).

Among perennial grasses are blue (*Bouteloua gracilis*), sideoats (*B. curtipendula*), slender (*B. repens*), and hairy (*B. hirsuta*) grama; bullgrass (*Muhlenbergia emersleyi*); common wolfstail (*Lycurys phleoides*); and Texas bluestem (*Schizachyrium cirratum*). Forbs include species of mariposa lily (*Calochortus* spp.), verbena (*Verbena* spp.), and lupine (*Lupinus* spp.). Beargrass or sacahuista (*Nolina microcarpa*), fairyduster (*Calliandra eriophylla*), common stool (*Dasylirion wheeleri*), pointleaf Manzanita (*Arctostaphylos pungens*), Fendler's ceanothus (*Ceanothus fendleri*), and Mexican cliffrose (*Purshia Mexicana*) are shrubs and half-shrubs in the understory. Shrub-forms of the oak species and mesquite are also present on many sites (Ffolliott et al. 2006b). Palmer's agave (*Agave palmeri*) is a scattered succulent. Annual plants are largely absent on the watersheds.

Additional information on vegetative, geologic, edaphic, and hydrologic characteristics of the watersheds is found in publications by Ffolliott and Gottfried (2010), Ffolliott et al. (2008b), Gottfried and Ffolliott (2013), Gottfried et al. (2012a, 2007b), Hendricks (1985), Neary and Gottfried (2004), Neary et al. (2008b), Osterkamp (1999), Robertson et al. (2002), Youberg and Ferguson (2001), and Vincent (1998).

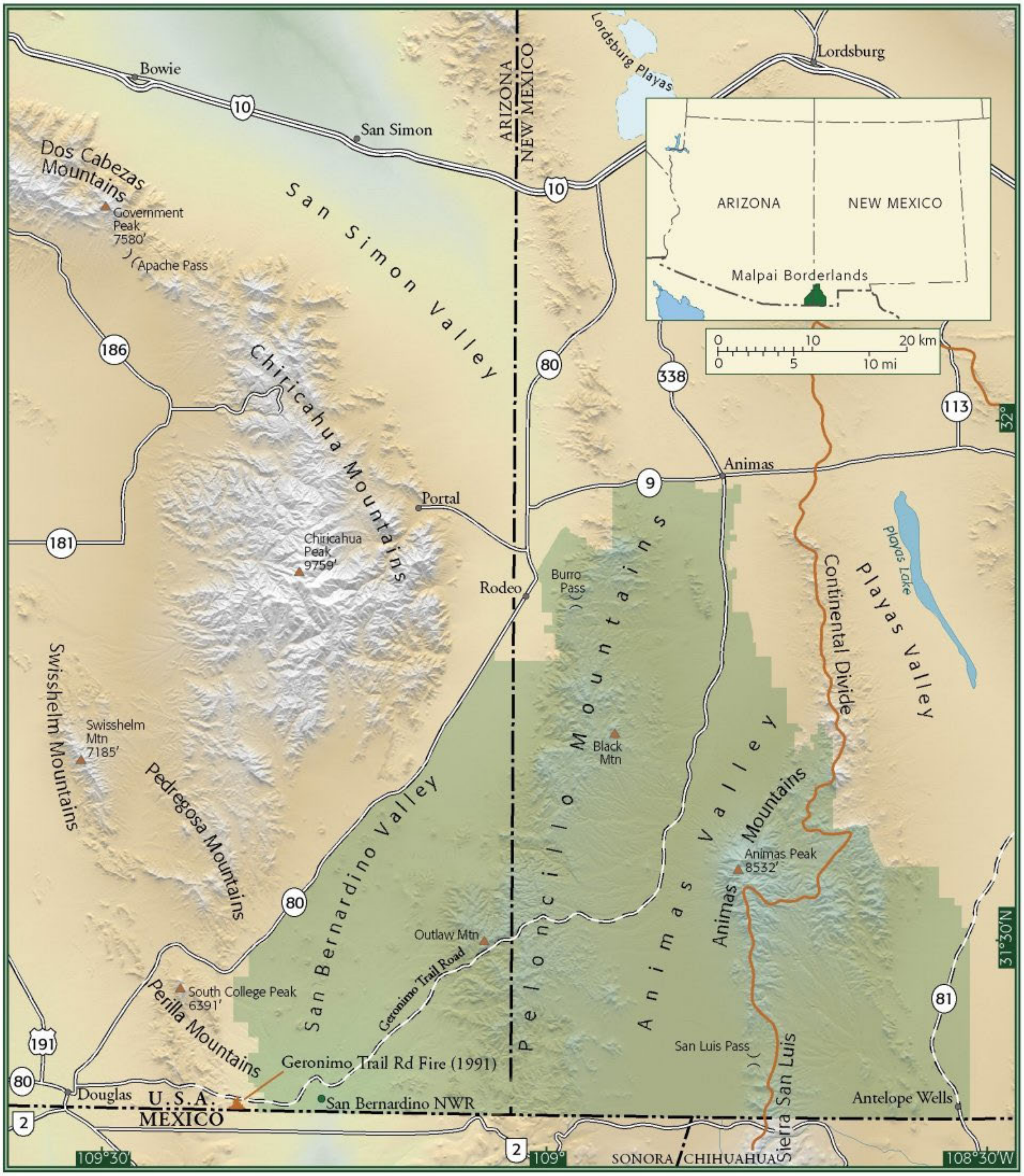

Figure 1. The Cascabel Watersheds (arrow) are located within the oak savannas of the Malpai Borderlands - an area of approximately 802,750 acres in the larger Southwestern Borderlands Region.

Table 1. Topographic characteristics of the Cascabel Watersheds, Peloncillo Unit, Coronado National Forest (From Gottfried et al 2000).

Watershed	Area	Average Elevation	Average Slope	Channel Length	Channel Slope	Watershed Length
	ac	ft	%	ft	%	ft
A	34	5552	22.8	1248	5.6	1434
B	37	5535	28.4	1938	7.0	2363
C	33	5530	17.5	797	2.5	1434
D	25	5510	17.1	956	6.3	1407
E	40	5503	18.5	2177	5.3	2549
F	31	5463	16.2	1407	6.0	1593
G	20	5460	17.4	743	6.7	1168
H	55	5562	18.7	1805	5.0	2443
I	83	5533	16.6	2522	3.8	3000
K	38	5503	16.2	2257	4.4	2469
M	45	5475	27.1	2177	4.1	2655
N	27	5485	9.0	1381	3.6	2124

Figure 2. Composition of tree species on the Cascabel Watersheds is representative of that found in the oak savannas of the region. Oak species are dominant in the tree overstory. (Photo by Daniel G. Neary, USDA Forest Service).

Research Program

The goal of the research program at Cascabel was to evaluate the effects of cool-season (November through April) and warm-season (May through October) prescribed burning treatments on ecosystem characteristics and hydrologic functioning (Gottfried et al. 2000, 2005, 2007a). It was anticipated that these evaluations would be compared to unburned (control) watersheds to determine the effects of the prescribed burning treatments. Following the required hydrologic calibration period, Watersheds C, H, K, and N (Figure 3) were burned in the cool-season in early March 2008. Three of the four watersheds designated for warm-season burning (Watersheds A, E, and F) were ignited on May 20, 2008 with burning of the fourth (Watershed I) delayed to a later date because of the shifting weather conditions. However, wind gusts up to 60 mph in the early morning of May 21 blew firebrands onto the remaining watershed scheduled for warm-season burning and the four control watersheds. The resulting wildfire - called the Whitmire Wildfire - crossed the boundaries of the Cascabel watersheds to burn almost 4,000 ac. As a result, the original goal of the research program was modified to evaluate the effects of cool-season and warm-season prescribed burning treatments and the Whitmire Wildfire on the biological and hydrologic resources of the watersheds (Figure 3).

The original study on the Cascabel Watersheds was to burn four watersheds by prescribed fire in the cool-season, to burn four watersheds in the warm season, and to keep four watersheds as unburned controls. It was necessary to modify this study design after the Whitmire Wildfire as shown in this figure. Watershed I was originally designated to be burned in the warm season but instead burned as a result of the wildfire. Atmospheric conditions during the prescribed burning treatments and wildfire are summarized in Table 2. The information presented in this table was obtained from a weather station located in the middle of the watersheds.

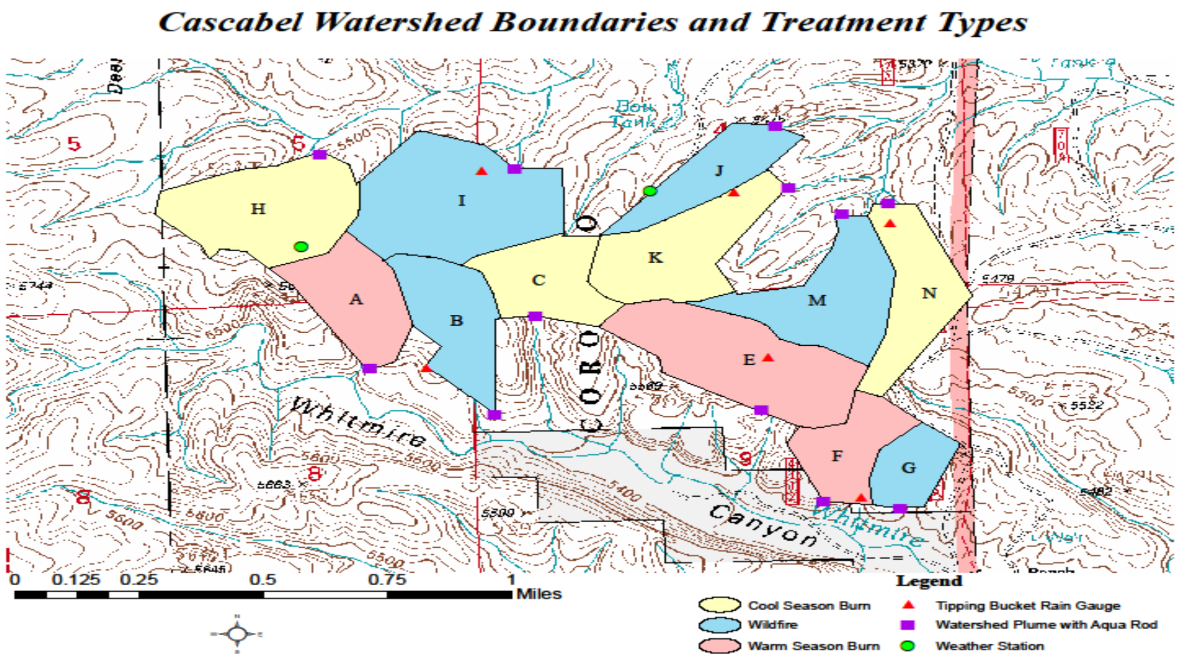

Figure 3. Cascabel Watersheds boundaries and treatments, Coronado National Forest (From Ffolliott et al. 2012).

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Severity of the Burning Events

A system that relates fire severity to the response of the soil-resource to burning events (Hungerford 1996) was the basis for assessing the severity of the prescribed burning treatments and wildfire within 0.10-acre plots at sampling locations on the watersheds (see Study Protocols section of this paper). This system relates the post-fire appearance of litter, duff, and woody materials and soil conditions to classes of fire severity that range from low to moderate to high.

Table 2. Average atmospheric conditions from 0700 to 1800 hours during the prescribed burning treatments and wildfire on the Cascabel Watersheds. The information presented in this table was obtained from a weather station located in the middle of the watersheds.

Treatment	Date	Temperature (°F)	Relative humidity (%)	Wind Speed (MPH)
Cool season	March 4	56.2	15.6	4.7
Cool season	March 11	62.5	20.2	3.4
Warm season	May 20	89.7	15.8	8.3
Wildfire begins	May 21	85.3	15.6	17.1

Details of the system are found in publications by Neary et al. (2005), DeBano et al. (1998). Classifications of fire severity at the plots were extrapolated to a watershed-basis to determine the percentages of each of the Cascabel Watersheds that were unburned or burned at low, moderate, or high severities.

These extrapolations indicated that 85 percent of the four watersheds burned by the cool season prescription had been exposed to a low severity fire; a moderate severity fire occurred on 5 percent of the watersheds; and 10 percent of the watersheds were unburned. Spatial distributions of fire severities on the three watersheds that experienced the warm-season prescription and the one watershed burned by the Whitmire Wildfire, and those burned in the wildfire were similar to the distributions of fire severities of the cool-season burn as shown in Figure 4. It was concluded, therefore, that the Cascabel Watersheds (collectively) had burned at a low severity by the three burning events. The low severities were attributed largely to the small and scattered accumulations of flammable fuels on the watersheds before the burning events and to the high wind-speeds during the burns.

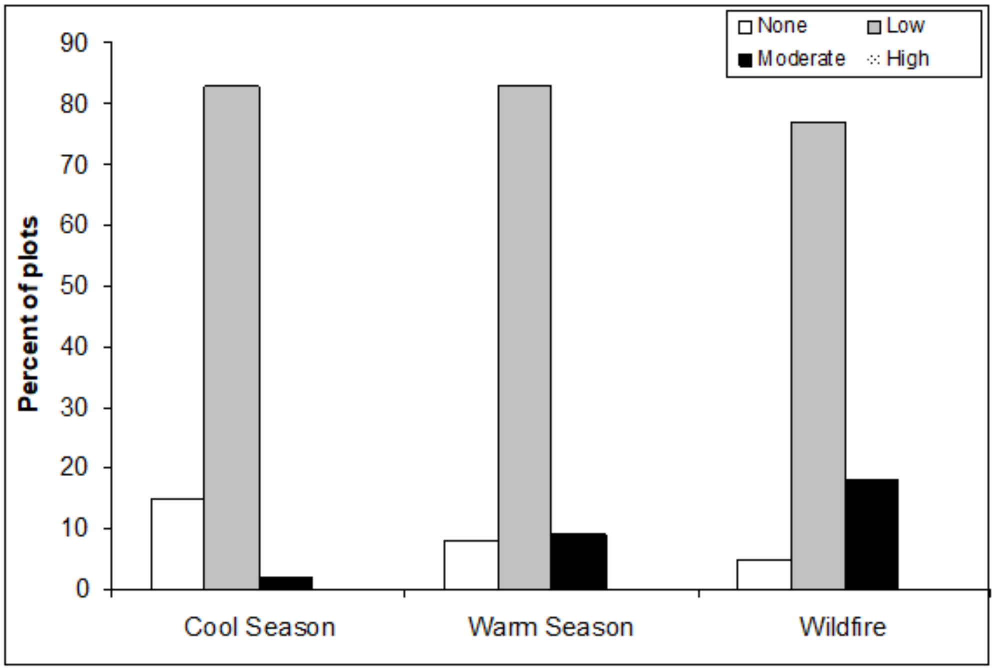

Figure 4. Fire severities of the cool-season and warm-season prescribed burning treatments and the Whitmire Wildfire on the Cascabel Watersheds based on the percent of the severities within 0.10-acre plots located at the sampling locations. Fire severities were derived from a classification system relating fire severity to the soil response to burning. These values were extrapolated to a watershed basis.

While high severity burns were not observed on the sampling locations, high fire severity occurred on scattered sites within the watersheds (Koestner et al. 2008a, Neary et al. 2008a, 2010). These sites were largely pockets where "heavy accumulations" of litter, duff, and other organic debris had built up before the burns. Fire combustion temperatures varied by season and vegetation type (Neary et al. 2010). Neary et al. (2010) reported mean temperatures during the cool season burn between 150°C for light grass and 292°C for heavy grass and maximum temperatures 997°C under yucca plants and 945°C under oak. Average combustion temperatures during the cool-season and warm-season burns were statistically similar. No measurements occurred during the wildfire.

STUDY PROTOCOLS

Between 35 and 45 permanent sampling locations were established on each of the 12 Cascabel Watersheds to measure ecological characteristics and hydrologic functioning and to monitor changes related to the fire events. These sampling locations were spaced along randomly-placed transects oriented perpendicular to the main stream channels and extending from ridge to ridge. Intervals between these sampling locations varied with the area and configuration (shape) of the watersheds. A total of 421 sampling locations were established on the 12 watersheds.

Precipitation Measurements

Precipitation is the main input in the water budget for an area. Therefore, two weather stations with recording gages were installed on the Cascabel Watersheds – one on the western edge of the watersheds and one on a side-ridge in the middle of the area. Precipitation, temperature, wind speed and direction, relative humidity, and other meteorological characteristics were measured at these weather stations (Figure 5) and the data was stored electronically and later downloaded to a computer and transferred to the Flagstaff Laboratory for review and analysis. The precipitation amounts measured at the weather stations was supplemented by measurements obtained at seven recording dipping-bucket gages situated throughout the area.

Hydrologic Functioning

Transpiration

Transpiration with evaporation represents the largest loss of precipitation falling on a watershed (Brooks et al. 2013), and, therefore, it is a key component in the water budget for oak ecosystems in the region (Ffolliott 2005). To quantify this component on the Cascabel Watersheds, instantaneous transpiration rates were measured on 16 Emory oak trees with a sap-flow meter (Swanson 1994) in late spring, summer, and early fall of 2004. Two of the trees selected for measurement were located on southerly aspects and two trees on northerly aspects on each of two transects of the sampling locations on two of the watersheds. The instantaneous measurements of transpiration obtained were transformed to estimates of daily transpiration by applying the equations of Schaeffer et al. (2000) and Barret et al. (1995), and the procedure outlined by Shipek et al. (2004).

Earlier studies of transpiration by oak trees in the oak woodlands of the region (Ffolliott et al. 2003, Ffolliott and Gottfried 1999) found that daily transpiration cycled throughout a year from high values following the summer and winter rains to intervening low values. There was a similar cycle of daily transpiration by Emory oak trees on the Cascabel Watersheds, and, therefore, this cycle was the basis to estimate annual transpiration of the 16 oak trees selected for measurement. It was also determined that the relationship of annual transpiration to the daily transpiration rate of oak trees in the earlier studies was representative of the Emory oak trees measured at Cascabel. This relationship was "coupled" with the frequency of occurrence of Emory oak trees with the respective vapor pressure deficit values on the watersheds to estimate annual transpiration in inches on an area basis.

Figure 5. One of the two weather station installed on the Cascabel Watersheds to measure precipitation and other meteorological characteristics. (Photo by Gerald Gottfried, USDA Forest Service).

Water Repellent Soils

Water repellent soils impact on the hydrologic functioning of a watershed by decreasing infiltration in a manner that is similar to a hardpan layer. Decreasing infiltration rates resulting from the formation of these soils can (in turn) increase overland flows of water and ultimately streamflows and the entrainment of soil particles in these flows. Distillation of organic compounds in the litter and duff layers in the combustion phase of a fire is one mechanism that causes the formation of water repellent soils (DeBano 1981, 2003). Therefore, the occurrence of water repellent soils after the burning events was determined within temporary 0.10 ac plots at the sampling locations by the water-drop penetration method of Letey et al. (2000) and applying the criteria specified by National Interagency Fire Center and outlined by Clark (2001). In applying these procedures, the litter and duff layers were cleared to expose the mineral soil, a drop of distilled water was placed on the mineral soil surface, and the time required for the drop to penetrate the soil surface recorded (Figure 6). This procedure was then repeated because the precise location of a water repellent layer (if a layer existed) was not known. The longest duration of the two times recorded for the water drop to penetrate the soil surface was related to the criteria of the National Interagency Fire Center to determine the level of water repellency - that is, no repellency; slight repellency – less than 10 seconds; moderate repellency - 10 to 40 seconds; or strong repellency - more than 40 seconds.

Hillslope Soil Erosion and Deposition

Soil erosion and deposition were measured on the hillslopes of the watersheds in the spring and fall both before and after the burning events. Spring measurements were indicative of the movement of soil by overland flows of water occurring in the winter while the fall measurements were a reflection of the soil movement resulting from overland flows in the summer. Obtaining these measurements involved measurements of three erosion pins surrounding every third sampling location. The magnitude of soil erosion was measured by the distance from the cap of a pin to the soil surface while deposition was the accumulation of soil on top of the cap (Figure 7). Measurements at the three pins were averaged to estimate soil erosion or deposition at the sampling location. After the measurements were taken, the erosion pins were re-set to be flush with the soil surface to facilitate the subsequent measurements. The magnitudes of soil erosion and deposition in the interval between the successive measurements were assumed equal when there was no measureable change in the soil surface relative to an erosion pin on occasion or - what is less likely - neither soil erosion nor deposition occurred in the interval. A bulk density value of 75 pounds per cubic foot developed from a series of soil samples on the watersheds was applied to convert the averages of the measurements of soil erosion and deposition obtained on the watersheds into tons per acre.

Figure 6. The time for a water droplet placed on a soil surface to penetrate into the surface is a measure of the level of water repellency of the soils at a sampling location. (Photo by Daniel G. Neary, USDA Forest Service)

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Figure 7. An erosion pin consisting of a metal nail with a washer welded to the top was inserted into the soil surface to measure soil erosion and deposition. The distance between the cap of the pin and the soil surface represented a measure of erosion while the amount of soil that accumulates on top of the cap was a measure of deposition. (Photo by Daniel G. Neary, USDA Forest Service).

Streamflow

Two prefabricated Parshall flumes were installed on each of the Cascabel Watersheds to monitor streamflow volumes and peak flows. A 9-inch flume with a rated flow capacity of 4.03 cubic feet per second (cfs) measured the more commonly encountered low flows while either a 3- or a 4-foot flume with flow capacities of 42.7 or 57.5 cfs, respectively, measured the less frequent larger flows (Figure 8). The smaller flumes were later converted to Replogle long-throated flumes to increase the accuracy of measuring low flows. Streamflow stages were measured by pressure-sensor recorders that were activated by stage-changes that equaled or were greater than 5 mm (approximately 0.2 in). The recorders were downloaded to laptop computers monthly with the data sets transferred to computers for analysis at the Southwest Forest Science Complex in Flagstaff, Arizona.

Figure 8. Two prefabricated Parshall flumes were installed on each of the Cascabel Watersheds to measure streamflow. A smaller flume measured low flows of water while the larger flume had a capacity to measure the infrequent larger flows. (Photo by Gerald Gottfried, USDA Forest Service).

Streamflow measurements began in 2001 to establish pre-fire relationships among the streamflows originating on the watersheds through regression analysis. These measurements represented the calibration period that was necessary before the burning treatments could be scheduled (Brooks et al. 2013). Once statistically acceptable relationships were obtained, the prescribed burning treatments were scheduled. Relationships of post-fire streamflow regressions are then compared to the pre-fire regressions to evaluate effects of the burns on streamflow regimes. Streamflow measurements on the watersheds continue.

Channel Erosion-Degradation: A series of cross-sections of stream channels above the flumes were measured in 2003, 2006, and 2009 to determine whether there were changes in channel morphology in the respective intervals. A total of 142 cross-sections located at 100 m (328 ft) intervals in the channels were measured at each time. More specifically, permanently referenced points along the cross-sections were surveyed with a level and stadia rod. An integration of sediment-degradation (incisions) processes was reflected by these measurements (Koestner et al. 2010, 2008b). Differences in the cross-sectional measures in the interval between 2003 and 2006 represented pre-fire conditions while post-fire conditions were embedded in differences measured in the interval between 2006 and 2009.

Sediment Depositions: A retention dam and basin were constructed above the flumes on each of the watersheds to accumulate the sediment particles deposited in the basins (Figure 9). Walls of the dams were tied into the channel sideslopes and had a spillway to allow high streamflow volumes to pass over. There was an average of 11 surveying lines in each basin that were reference to a permanent benchmark. A series of permanently referenced points on these lines were surveyed to measure the accumulations of sediment in the basin. Volumes and the volume differences between surveys were calculated by the WinXSPRO program (Hardy et al. 2005) and the average end-area method of Dendy et al. (1979). An average bulk density value of 69.3 pounds per cubic foot representing a composite of values obtained from the literature was used to also express the cubic-foot volumes of sediment depositions in corresponding measures in tons.

Figure 9. A sediment basin was located above the flumes on each of the Cascabel Watersheds to accumulate sediment that is deposited near the outlets of the watersheds. (Photo by Daniel Neary, USDA Forest Service).

EFFECTS OF THE BURNING EVENTS ON HYDROLOGIC FUNCTIONING

Transpiration

Annual transpiration of oak trees on the Cascabel Watersheds was 4.8 inches of water or approximately 30 percent of the assumed annual precipitation. The effect of thinning post-harvesting rootstocks of oak trees in the woodlands to three, two, or one basal sprout on annual transpiration is presented in Table 3. While transpiration of an individual stump sprout was small, the large number of stump sprouts in the harvested stand translated into larger transpiration values regardless of the thinning treatment (Ffolliott and Gottfried 1999). Effect of the burning events on transpiration rates of sampled oak trees was not measured. However, it was assumed to be "slightly" less than transpiration before the burns because of the minimal loss of trees in the fires (Figure 10).

Table 3—Annual transpiration in stands of thinned Emory oak coppice and the percent of annual precipitation transpired by the coppice in 2001 (Ffolliott et al. 2003, and Shipek et al. (2004).

Thinning Treatment	Daily Transpiration	Total Transpiration per Unit Area of Coppice	Total Transpiration Coppice Plus Trees	Annual Rainfall Transpiration 2001
	L	**mm yr^{-1}**	**mm yr-1**	**%**
One Sprout	7.48 ± 0.31	68	181	33.5
Two Sprouts	17.7 ± 0/86	160	273	50.5
Three Sprouts	23.7 ± 1.12	215	328	60.7
Control	35.3 ± 1.72	320	433	80.2

*Estimated transpiration for mature Emory oak trees was 17.5 L/day (Shipek et al. 2004)

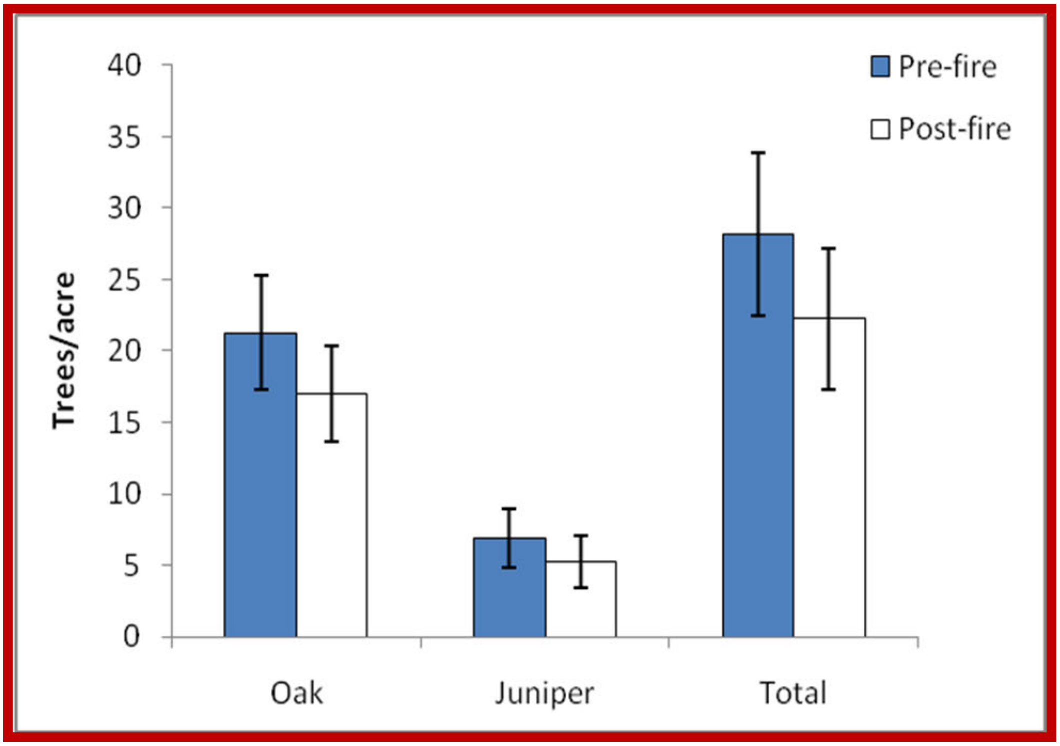

Figure 10. Average number of oak and juniper trees per acre before and after prescribed fires and wildfire.

Ground Cover

Bedrock, fine sediment, coarse sediment, vegetation, and woody debris were the largest components of ground cover before the burns with the percentages of bare soil significantly less than these components (Ffolliott et al. 2012a) Differences in ground cover components following the burning events were insignificant and, therefore, pooled for analysis. There were significant increases in the percentages of plant material and bedrock following the burning events while the percentages of litter and bare soil decreased. The increase in plant material was largely the result of the increase in downed woody material that is included in the component. The changes in ground cover following the burns were likely inconsequential in terms of the hydrologic functioning of the watersheds (Ffolliott et al. 2012a). The measure of ground cover decreased from 75 percent before the watersheds were burned to 67 percent after the burning events. This small change by itself should not impact on future management actions on the watersheds.

Water Repellent Soils

Water repellent soils that formed as a result of the burning events were limited in both occurrence and level of repellency and confined mostly to the soil surface. No water repellency was found on about 90 percent of the sampling locations, slight water repellency on 5 percent of the locations, and moderate or strong repellency on the remaining locations (Stropki et al. 2009) (Figure 6). The limited occurrence and low levels of water repellent soils were expected because the low severity of the burns constrained formation of water repellent soils (Figure 11). However, Neary et al. (2006) reported high levels of water repellency in isolated locations within the prescribed burned areas usually associated with fuel accumulations.

Occurrences and the levels of water repellent soils have been related to fire severities in other studies with a greater occurrence and higher level of repellency associated with higher fire severities (Huffman et al. 2001, Doerr et al. 2000, DeBano 1981, 2000). But, because of the low levels of water repellency on the Cascabel Watersheds, such a relationship was not observed in this study. Furthermore, the water repellent soils on the watersheds had mostly broken down within a year of the burning events by a downward erosion of the hydrophobic layers until they had eroded away. It has been concluded, therefore, that the water repellency that had formed following the burns had little lasting impact on the hydrologic functioning of the watersheds.

Hillslope Soil Erosion and Deposition

Hillslope soil erosion and deposition in channels were analyzed separately because they represent separate processes of soil movement. Results of a Shapiro-Wilk test of normality that the frequency distributions for both soil erosion and deposition were non-normal. Therefore, occurrences of statistical differences in the measurements were determined by the non-parametric Mann-Whitney test of significance. This test was applied because estimates of the respective processes were deemed independent of each other. It was found that there were no significant differences in either soil erosion or deposition at the 0.10 level of significance either before or after the burning events and, therefore, the respective data sets were pooled for analysis.

Soil Erosion

Differences in soil erosion measurements in the spring following the winter rains and measurements in the fall after the summer rains were insignificant before the burning events. Annual hillslope soil erosion in this period averaged 14.2 tons per acre across the 12 watersheds. Examples from Watersheds A and I, which cover the geomorphic gradient, are shown in Figure 12. Thes pre-fire values show some f the inter-watershed variability. However, soil erosion following the burns was greater than pre-fire soil erosion following the winter rains but lower after the summer rains. The seasonal measurements of post-fire soil erosion appeared to “balanced” each other out on an annual basis because there was no significant difference in annual soil erosion as a result of the burns.

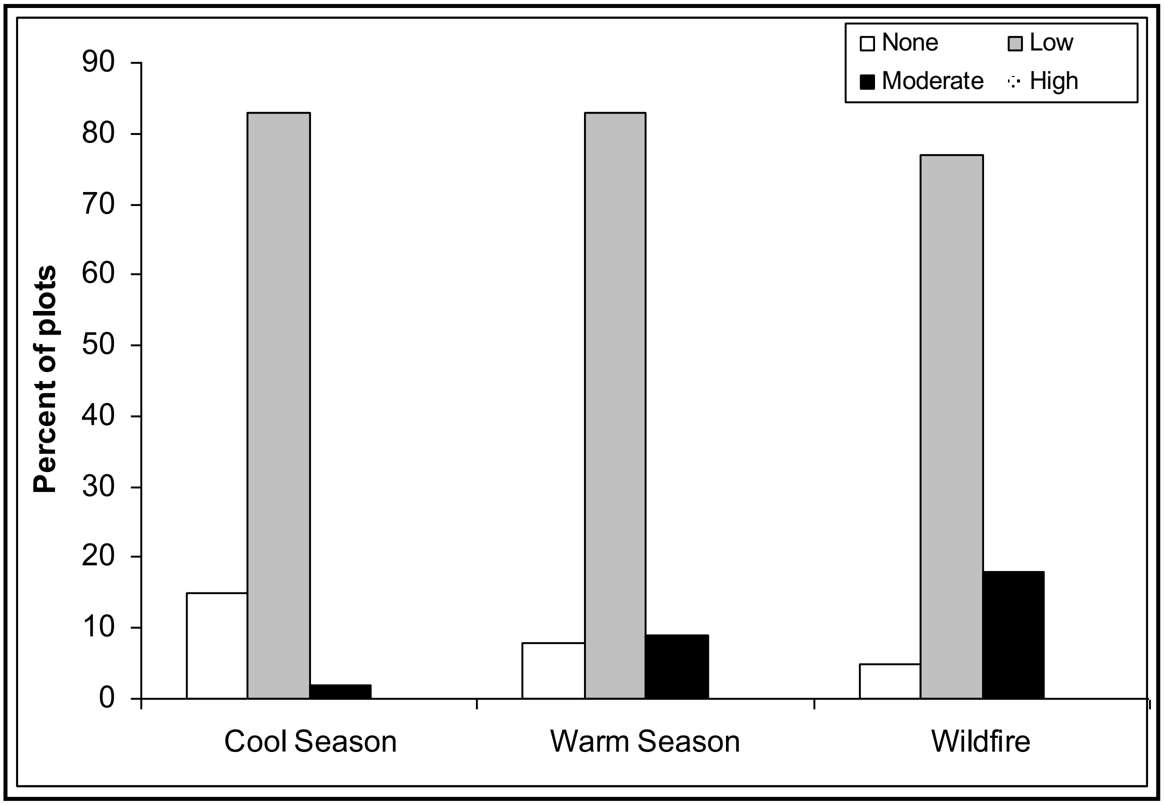

Figure 11. Severities of three fire situations on the 12 Cascabel Watersheds, Coronado National Forest. Arizona.

Table 4. Soil erosion from side slopes of Cascabel Watersheds A and I in Spring and Fall measurements of 2005.

Watershed	Spring 2005	Fall2005	Total
	Tons ac^{-1}	Tons ac^{-1}	Tons ac^{-1}
A	9.94 ± 1.25	10.80 ± 2.33	20.74
I	17.70 ± 1.25	4.62 ± 0.95	22.32
Total	27.64	15.42	

That the annual erosion of soil after the burning events was within the range of the pre-fire value was a result of similar erosive forces caused by the impacts of rain drops in the two periods. Absence of widespread water repellent soils after the burns, and the likelihood of little change in the overland flows of water necessary to dislodge soil particles on the hillslopes of the watersheds also contributed to this finding.

There were no significant relationships between the magnitudes of soil erosion and the rainstorm events necessary to generate overland flows of water or the characteristics of vegetation at the sampling locations. However, soil erosion was significantly less on the upper slopes of the watersheds than on the lower slopes. This finding could be attributed to a possibility of “thinner soil profiles” on the upper slopes. Unfortunately, measurements of soil depths on the slopes of the watersheds are not available to confirm this possibility.

Deposition

Deposition of soil after the winter rains was also compared to the deposition following the summer rainstorms to determine whether seasonal differences occurred before the burning events. It was determined that while the deposition of soil after the winter rains differed from the deposition following the summer rains, the differences in deposition within the seasons and years were inconsistent. Annual deposition of soil before the burns averaged 6.3 tons per. However, post-fire deposition of soil after the winter rains was statistically similar to the pre-fire deposition but was significantly greater following the summer rains for an unknown reason. Annual deposition of soil after the burns averaging 9.4 tons per acre was also greater because of the difference in deposition measured following the summer rains. Depositions of soil were not related to rainstorms or vegetation at the sampling locations. While there were significantly greater depositions of soil on the lower slopes than on the upper slopes of the watersheds before the burning events, there was little relationship of the depositions to slope position following the burns.

Streamflow

Streamflow originating on the Cascabel Watersheds is intermittent rather than ephemeral because most of the streamflow events are a response to either summer or winter rainstorms and cease at other times. (Strictly speaking, the intermittent streamflow that takes place is "stormflow" in that it occurs in response to a rainfall event of sufficient magnitude to satisfy the soil-water deficits on a watershed or a sequence of smaller rainfall events that in total satisfy these deficits.) A limited number of streamflow events occurred on the watersheds both before and after the prescribed burning treatments and wildfire. That few flows were observed was due to the drought conditions encountered throughout the period of record.

Variability of Streamflow Volumes and Peaks

Watersheds in arid and semiarid regions generally have lower infiltration capacities and shallower soils with lower capacities to store soil moisture than watersheds in more humid regions (Brooks et al. 2013). Therefore, watersheds such as those at Cascabel would be expected to respond more quickly to streamflow-generating rainstorms with comparatively more variable streamflow volumes and peaks than watersheds in other regions. Such has been the case on the Cascabel Watersheds with a "high level of variability" in the recorded streamflow volumes and peaks since the stream-gauging network became operational. Gottfried et al. (2007) attributed much of this variability to the meteorological characteristics of the streamflow-generating rainstorms; the geology, geomorphology, and soils of the watersheds; and the orientation of the watersheds relative to the track (movement) of the streamflow-generating storms. Comparisons of pre- to post-fire streamflow regimes were often inconclusive because of the high variability in the respective data sets.

Effect of Large High-Intensity Rainstorm on Streamflow

Analysis of the streamflow response to a large high-intensity rainstorm on August 23, 2005 by Gottfried et al. (2006) provides insight on the effects of a storm of this magnitude on streamflow volumes and peaks. Total rainfall in this storm - one of the largest in the Cascabel period of record – varied across the watersheds from 1.36 in to nearly 3 in with the highest rainfall intensities ranging from 1.90 to 3.31 in hr^{-1} (Tables 5 and 6). Because a series of smaller storms on August 10, 11, 14, and 20 had likely satisfied the soil-moisture deficits on the watersheds, antecedent soil moisture conditions on the watersheds were "relatively high" before the storm of August 23. It was not surprising, therefore, that the storm generated streamflow volumes that overtopped the larger flumes on four of the watersheds.

Highest estimated streamflow peak resulting from the storm was 2.75 m^3 sec^{-1} (76.8 ft^3 sec^{-1}) on Watershed H while the smallest peak was 0.906 m^3 sec^{-1} (32 ft^3 sec^{-1}) on Watershed F. (Streamflow peaks were estimated on the watersheds with overtopped flumes from channel and slope measurements.) A reason for this range in streamflow peaks could have been the respective times of concentration for the watersheds; that is, the time required for the entire watersheds to contribute streamflow at their outlets. Watershed H is nearly 1.8 times larger in area than Watershed F. Channel conditions would also affect the times of concentration (Neary and Gottfried 2004). The channel on Watershed H is 11 percent rock and 68 percent coarse alluvium while the channel on Watershed F is 21 percent rock and 42 percent coarse alluvium.

Table 5. Precipitation for the storm event of August 23, 2005, by watershed.

Station	Total Precipitation	Start Time	End Time	Peak Precipitation
	in (mm)	MST	MST	in hr^{-1} (mm hr^{-1})
H	2.36 (59.94)	1200	1600	1.90 (48.26)
J2	2.33 (59.18)	1200	1600	1.93 (49.02)
A-B	2.64 (67.06)	1201	1544	2.94 (74.68)
E	2.03 (51.56)	1212	1552	2.24 (56;90)
F-G	1.36 (34.54)	1209	1549	1.52 (38.61)
I	2.99 (75.95)	1206	1547	3.31 (84.07)
K	2.81 (71.37)	1213	1602	3.19 (79.75)
M-N	1.43 (36.32)	1221	1552	1.98 (50.29)

Table 6. Peak flows from the Cascabel Watersheds for the August 23, 2005, storm event.

South Watersheds	Peak Flow	North Watersheds	Peak Flow
	ft^3 sec^{-1} (m^3 sec^{-1})		ft^3 sec^{-1} (m^3 sec^{-1})
A	67.2 (1.90)	H	76.8 (2.17)
B	69.0 (1.95)	I	52.6 (1.49)
C	51.2 (1.45)	J2	61.9 (1.75)
E	59.8 (1.69)	K	67.9 (1.92)
F	24.6 (0.70)	M	65.0 (1.84)
G	34.0 (0.96)	N	31.3 (0.59)

Channel Erosion-Degradation

None of the burning events had an apparent effect on the erosion-degradation processes of the stream channels. Although there is a great variability among the channels on the 12 watersheds, Koestner (2012) concluded that the channels were not at risk to these processes because of the bedrock-lined channels on the watersheds. It was also possible that the limited streamflow events that occurred between the consecutive measurements of channel cross-sections might have been insufficient in the totality of their "erosive power" to impact on the morphology of the stream channels (Figure 13). That is, the soil particles entrained in these episodic streamflow-events were likely insufficient their magnitude, size, and shape to significantly erode the channels.

Possible changes in channel morphology were difficult to evaluate, however, because the intervals between successive measurements of the channel cross-sections could have obscured changes that might have occurred in a channel at a point in time within an interval. Also, effects of the burning events on channel morphology could not be isolated because the interval between the 2006 and 2009 measurements integrated conditions occurring both before and after the burns.

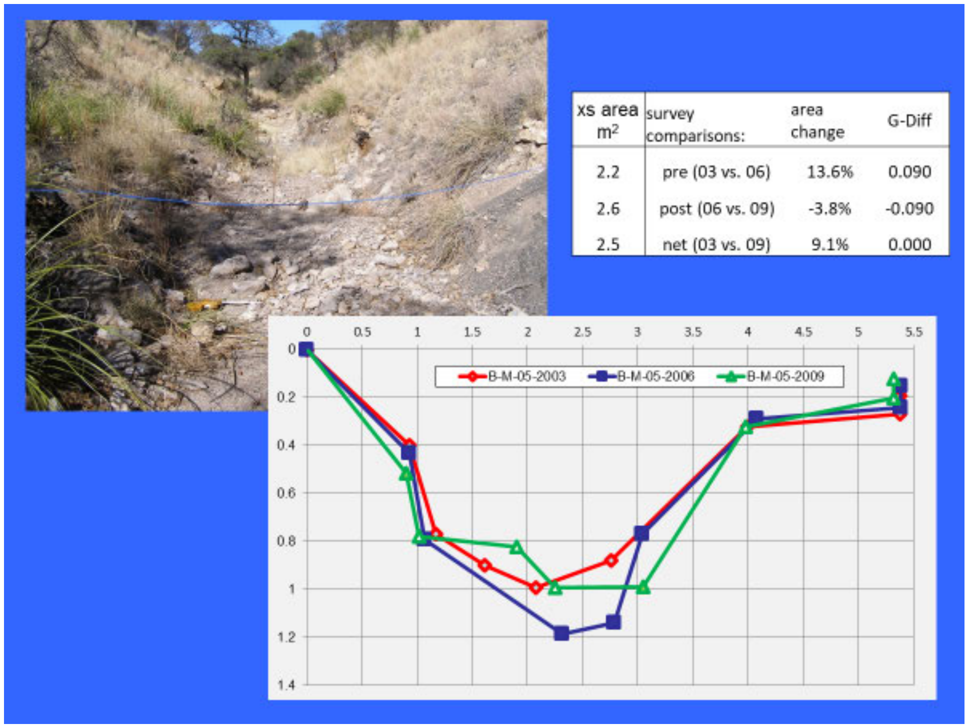

Figure 12. Cross-section measurements of the stream channel of a Cascabel Watershed made in 2003, 2006, and 2009. The cross-section measurements in the intervals shown indicate the lack of a significant effect on erosion-degradation of the stream channels of the watershed. (Photo by Daniel Neary, USDA Forest Service; Graph by Karen Koestner, USDA Forest Service).

Sediment Depositions

Soil particles that had eroded from one site on a hillslope were either deposited downslope on another hillslope site or transported to a stream channel to accumulate as sediment. Depositions of sediment particles in a sediment basin were affected by the proximity of the source of soil erosion to the basin; the size-class distributions of soil particles entrained in overland flows of water; and the efficiency of moving the sediment particles from one part of a basin to another. Accumulations of sediment were also reflected by the re-distribution of sediment particles in the overland flows of water.

Measurements of the sediment accumulations behind the dams forming the sediment basins provide a perspective on the magnitude of sediment depositions as shown in Figure 13. (The amount of entrained sediment passing over the spillways of the dams in the occasional large streamflow events is unknown and, therefore, cannot be included in the sediment budgets for the watersheds.) The deposition of sediment in the basin on Watershed A was measured for the 20-month period of August 2003 to March 2005 – when the sediment accumulation to the point in time was measured and the removed from the basin - and for the 10 months between April 2005 and January 2006. Approximately 52.2 cubic feet (1.8 tons) of sediment were deposited in the first period while 190 cubic feet (6.6 tons) of sediment had accumulated in the second period that included the large high-intensity rainstorm of August 23, 2005 (see Streamflow section of this paper). On an annual basis, these totals were equivalent to 31.3 ft^3 (1.1 tons) and 218 ft^3 (7.6 tons) per year, respectively. The deposition of sediment in the basin on Watershed I for the one period of December 2003 to January 2006 was 190.3 ft^3 (6.6 tons) or 91.5 ft^3 (3.1 tons) per year.

Figure 13. Sediment accumulating behind one of the sediment dams forming the sediment basins provides a perspective of the range of sediment textures in depositions in the watershed channels (Photo by Daniel G. Neary, USDA Forest Service, Rocky Muntain Research Station).

There was little relationship between the accumulations of sediment in the basins of the two watersheds and the volume of soil eroded from the hillslopes of the watersheds that might have been deposited in the basins in the corresponding periods of time. (This latter value was approximated as the difference in the soil erosion and deposition on the hillslopes of the watersheds in the respective time periods.) Contribution to the sediment accumulations by channel erosion-degradation processes was negligible.

Additional Information on Hydrologic Functioning

Additional information on the general hydrology of the Cascabel Watersheds including precipitation patterns are found in Gottfried et al. (2014, 2012b, 2007b). References containing additional information on the transpiration of oak trees in the region are Ffolliott et al. (2003) and Shipek et al. (2004). More details on the formation of water repellent soils as a result of the burning events are presented in Neary et al. (2008a) and Stropki et al. (2009). Further comparisons of hillslope soil erosion and deposition are found in publications by Ffolliott et al. (2013, 2010a), Kauffman (2009), and Kauffman et al. (2007). Gottfried et al. (2014, 2007b, 2006) present additional information on streamflow regimes of the watersheds. More details of the channel erosion-deposition processes are found in (Koestner 2012) and Koestner et al. (2008b, 2010). Further information on sediment depositions can be obtained in Gottfried et al. (2014).

Hydrologic Functioning

Annual transpiration by a sample of Emory oak trees before the burning events was 30 percent of annual precipitation – a value that was less than that for Emory oak trees in the more densely-stocked oak woodlands of the region. While the effect of the burns on the transpiration rates of oak trees was not determined directly, it was likely somewhat less than before the burns because of the minimal loss of trees in the fires. Water repellent soils that formed as a result of the low-severity burns were largely broken down within one year and, therefore, were assumed to have a minimal impact on the hydrologic functioning of the watersheds. Effects on the burning events on hillslope soil erosion and deposition were minimal. However, both pre- and post-fire soil erosion and deposition were measured in a period of prolonged drought.

The regional drought has limited the number of streamflow events that can be analyzed to ascertain any effects of the fire treatments on streamflow volumes and quantities. Variability of the intermittent streamflow volumes and peaks originating on the watersheds also limited a comparison of streamflow regimes before and after the burning events. However, a large high-intensity, summer rainstorm generated streamflow volumes that overtopped the larger flumes on four of the watersheds provides insight on the streamflow regimes. None of the burning events had a measureable effect on the erosion-degradation processes of the bedrock-lined stream channels. The limited number of streamflow events that have occurred might have been insufficient in total to significantly impact on the morphology of the stream channels. There was little relationship between accumulations of sediment in the sediment basins and the estimated volume of soil particles eroded from the hillslopes that reached the channels. The contribution of channel erosion-degradation to sediment depositions was negligible.

SUMMARY AND CONCLUSIONS

Management Implications

Information presented in this paper should be useful to land managers, local stakeholders, and other decision-makers interested in the re-introduction of a historical fire regime into the oak savannas of the Southwestern Borderlands Region. More specifically, the overcrowding of trees in the overstories; the accompanying decrease in production of herbaceous plants including forage species in the understories; the loss of wildlife habitats; and the often excessive loading of flammable fuels that are found on some sites could be alleviated to some extent by prescribed burning treatments of low severity at specified temporal intervals. Moreover, effects of these treatments on the hydrologic cycle and functioning of the oak savannas will likely be minimal. However, fire specialists should view the findings obtained at Cascabel as a case study. It should be recognized that prescribed burns of low severity - such as those on the Cascabel Watersheds - on other sites in the oak savannas of the region might not "produce" the same results as those reported in this paper. Additional evaluations of the impacts of prescribed burning treatments of varying intensities and severities and seasonal timing of ignitions on ecological characteristics and hydrologic functioning will be necessary to formulate comprehensive and effective management strategies to achieve the desired benefits on other sites. A change in protocols for implementing prescribed burning treatments in "less restrictive" weather and other fuel conditions might also be considered.

Of increasing interest to people in the Southwestern Borderlands Region and elsewhere are the effects that possible climatic changes might exert on ecological, hydrological, and socio-economic conditions. Climatic models suggest that air temperatures should increase, precipitation amounts will fluctuate, and "extreme weather events" might increase in the southwestern United States as a consequence of climatic changes (Archer and Predick 2008, Seager et al. 2007). Assuming that these changes occur, the compositions, densities, and viability of less drought-tolerant species of plants and animals are likely to be altered with some species disappearing and replaced by more drought-tolerant invasive species. A warmer and drier climate would also limit the water resources available for people while increasing the potential for more frequent and larger wildfires. The Cascabel Watersheds – with more than 10 years of meteorological, ecological, and hydrological information available – represent an ideal site for monitoring and evaluating the effects of possible climatic changes in the region (Gottfried et al. 2014, 2012). This information might also be combined with similar information obtained from other sites within the region to provide a more holistic view of the potential impacts of climatic changes on people and natural resources in the greater Southwestern Borderlands Region.

ACKNOWLEDGEMENTS

This research program on the Cascabel Watersheds was supported by the Southwestern Borderlands Ecosystem Management Unit of the Rocky Mountain Research Station, USDA. Forest Service, Phoenix, Arizona; the U.S. Forest Service National Fire Plan; the USDA Natural Resources Conservation Service, Douglas; the Douglas Ranger District of the Coronado National Forest; and the Arizona Agriculture Experiment Station, University of Arizona, Tucson, Arizona. The cooperation of personnel at the Diamond A Ranch, New Mexico, in the research program at Cascabel is greatly appreciated. The authors of this paper gratefully acknowledge the invaluable field and analytical assistance provided by Larry Telles, John Yazzie, Jackson Leonard, Karen and Peter Koestner, and Z. Lucene, of the Rocky Mountain Research Station of the U.S. Forest Service; Sam Smith of Landscape Restoration, Inc.; and Cody Stropki, Catlow Sipek, Hui Chen, Aaron Kauffman, Wendy and Carl Jones, Jeremy Doschka, Jolie Goldenetz, Beth Williams, and Steve Woods of the School of Natural Resources and the Environment of the University of Arizona. The authors also thank the members of the Fire Crew from the Douglas Ranger District of the Coronado National Forests for planning and implementing the prescribed burning treatments in this study, and the staff of the U.S. Fish and Wildlife Service, San Bernardino Wildlife Refuge for help during the burning. The inspiration and mentoring of Dr. Peter Ffolliott (Deceased) and Dr. Leonard DeBano (Deceased) were of great value. They are greatly missed.

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