FIRE EFFECTS ON SOIL EROSION AND DEPOSITION ON HILLSLOPES IN THE OAK SAVANNAS

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Fire was a natural occurrence in many ecosystems of the Southwest Borderlands before Euro-American settlement. However, natural fire frequencies and the burning characteristics of the fires have been altered since the early 1900s, largely because of past livestock grazing practices, which removed significant portions of the fire-carrying herbaceous vegetation, and past fire suppression policies of land management agencies (Edminster et al. 2000, Fulé and Covington 1995). These practices and policies have resulted in over-crowding of tree overstories on many sites, with the trees more susceptible to insects, disease, and wildfire. Mesquite (*Prosopis* spp.) and other woody plants have invaded otherwise productive grassland ecosystems in many instances. As a consequence of these conditions, land management agencies, with support from collaborating universities, private-sector organizations, and local stakeholders, are exploring the possibilities of re-introducing "more natural" fire regimes into many of the ecosystems in this region. Included among these ecosystems are the oak savannas, a plant community situated between the higher-elevation and more densely stocked oak woodlands and lower-elevation desert grassland-shrub vegetation.

Pre-fire estimates of soil erosion and deposition and an initial analysis of the effects of prescribed burning treatments and a wildfire on soil erosion and deposition in the oak savannas of the Malpai Borderlands are presented in this paper. This information should be useful in preparing strategies for re-introduction of "more natural" fire regimes into this region.

CASCABEL WATERSHEDS

Twelve small watersheds, ranging from 20 to almost 60 acres in size, in the Peloncillo Mountains of southwestern New Mexico (Gottfried et al. 2000, Gottfried and Edminster 2005) were (collectively) the study areas. The areal aggregation of these watersheds, called the Cascabel Watersheds, is 451.3 acres. The watersheds are situated between 5,380 and 5,590 feet in elevation. The nearest long-term precipitation station indicates that annual precipitation averages 23.5 inches, with nearly one-half occurring in summer rainfall. Streamflow originating on the watersheds is intermittent. However, large flows can be generated by high-intensity rainfall events (Gottfried et al. 2006). Vegetative, geologic, physiologic, and hydrologic characteristics of the watersheds are described elsewhere (Ffolliott and Gottfried 2005, Ffolliott et al. 2008, Gottfried et al. 2000, 2007, Neary and Gottfried 2004, Osterkamp 1999, Robertson et al. 2002, Vincent 1998, and Youberg and Ferguson 2001) and, therefore, not presented in this paper.

PRESCRIBED FIRE TREATMENTS AND WILDFIRE

The original objective of the research program on the Cascabel Watersheds was to evaluate the effects of warm-season (May through October) and cool-season (November through April) prescribed burning treatments on the natural resources including the tree overstories, herbaceous understories, wildlife populations and their habitats, erosion and deposition on the hillslopes and consequent sedimentation, and stormflow regimes. These evaluations would then be compared to unburned (control) watersheds to assess the impacts of the burning treatments. Following the required calibration period, four of the watersheds were burned during the cool-season in early March 2008. Three of the four watersheds to be burned in the warm-season were successfully burned on May 20, 2008, with burning of the fourth watershed scheduled for a later date. However, wind gusts up to 60 mph blew firebrands (burning embers) onto the remaining watershed to be burned and the four control watersheds in the morning of May 21, 2008. The resulting wildfire, designed the Whitmire Wildfire,

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crossed the boundary lines among the watersheds and spread outward to burn approximately 4,000 acres.

The original objective of the research program on the watersheds had to be modified as a consequence of the wildfire. The current program is to accomplish the original objectives by evaluating the effects of cool-season and warm-season prescribed burning treatments and wildfire on the natural resources considered originally.

CLASSIFICATION OF FIRE SEVERITY

A system that relates fire severity to the soil-resource response to burning (Hungerford 1996) was the basis for classifying severity of the cool-season and warm-season prescribed burning treatments and wildfire at the sample plots located on the watersheds (see below) following the tree burning events. Classifications of fire severity at the sample plots were then extrapolated to a watershed-basis to determine the respective percentage of the Cascabel Watersheds that were burned at low, moderate, and high fired severities by the prescribed burns and wildfire.

These extrapolations indicated that 85 percent of the four watersheds experiencing the cool-season prescribed burn had been exposed to a low severity fire, a moderate fire severity was observed on 5 percent, and the remaining 10 percent were unburned (Stropki et al. 2009). Distributions of fire severities on the three watersheds exposed to the warm-season prescribed burn were similar generally to those of the cool-season burn. Three-fourths of the five watersheds burned by the wildfire had been exposed to a low severity fire, 20 percent to a moderate fire severity, and no burning effects were observed on 5 percent of the watersheds. It was concluded, therefore, that the Cascabel Watersheds burned by the prescribed treatments and wildfire had all been exposed to burning events of low severities.

STUDY PROTOCOLS

Sampling Basis

On each of the Cascabel Watersheds, between 35 and 45 sample plots had been located along transects perpendicular to the main stream systems and situated from ridge to ridge to provide the sampling basis for obtaining pre-burning data sets on the natural resources to be evaluated. The interval between the plots varied depending on the size and configuration of the watershed sampled. A total of 421 plots were located on the 12 watersheds. This basic sampling design had been used in other (earlier) studies of the natural resources on the Cascabel Watersheds (including Ffolliott and Gottfried 2005, Ffolliott et al. 2005, 2008, Gottfried et al. 2007, Jones et al. 2005, and Stropki et al. 2009).

Measurements of Soil Erosion and Deposition

Three capped pins were placed around every third plot on the watersheds to measure soil erosion and deposition. Two pins were placed 3 feet upslope and one pin 3 feet downslope of a plot. Seasonal measurements of soil loss beneath the cap of the pins (soil erosion) or soil accumulation on the cap if the pins (soil deposition) were made in the spring and fall to characterize soil movements following periods of winter rains and summer rainfalls, respectively. Occasionally, there was no measurable change in the soil surface beneath the cap. It was assumed in these cases that either the magnitudes of soil erosion and deposition in the time interval between the measurements equaled each other or (what is less likely) neither erosion nor deposition occurred in the time interval. The capped pins were re-set flush to the soil surface after each measurement to facilitate the subsequent measurements. Measurements obtained from the three pins surrounding a plot were averaged to estimate soil movement at the plot, with the plots on a watershed then averaged to described soil erosion and deposition on a watershed-basis.

Initial measurements were made in the fall of 2004 (Ffolliott et al. 2005) with pre-fire measurements continuing on a biannual basis until the burning events on the Cascabel Watersheds occurred. Post-fire measurements were made initially in the spring of 2008 shortly following the cool-season burns, with post-fire measurements of all three burning events made in the fall of 2008 and spring and fall of 2009. A bulk density value of 70.5 pounds/cubic-foot was used in converting the measurements of soil erosion and deposition to corresponding measures of tons per acre on a watershed-basis.

Measurements of soil erosion and deposition were analyzed separately as they represented separate processes of soil movements on the hillslopes of the watersheds. Because the frequency distributions of the two data sets were non-normal in structure and transformations of the data sets failed to normalize the distributions, the respective measurements of soil erosion and deposition were analyzed by "distribution-free" non-parametric tests, namely the Mann-Whitney and Nemenyi tests. These tests are outlined in Zar (1999) and other references on non-parametric methods of statistical analyses. Plots with no measurable change in soil movement were excluded from the analysis. All of the comparisons were evaluated at a 0.10 level of significance.

Other Measurements

Determining whether soil erosion or deposition might be related to precipitation, physiography, and/or vegetation on the watersheds was a study component. Rainfall amounts recorded at two weather stations located on the watersheds were averaged for each measurement period to determined if these seasonal amounts related to soil movement. Rainfall intensities were also determined from these records. High-intensity rainfall events can result in detachment of soil particles and subsequent downslope movement of the particles. However, the detachment of soil particles by the impact of raindrops is not necessarily a "proxy" of soil movement alone. Consideration of overland flows of water is also required (Parsons et al. 1999). Following a review of studies on the characteristics of rainfall events and resulting overland flows of water, Syed et al. (2003) selected a rainfall intensity of 0.25 inches/hours as a "minimum threshold" for generating overland flows in the region. This threshold was selected for the analysis of soil erosion and deposition on the Cascabel Watersheds in this study.

Rainfall amounts inducing overland flows of water was also considered as a possible variable related to soil movement. Osborn and Lane (1969) reported that individual rainfall events totaling 0.32 inches resulted in overland flows of water on the Lucky Hills Watershed near Tombstone, Arizona. Because of the "shallow" soils characterizing the Cascabel Watersheds, rainfall events of 0.35 inches or more were selected (arbitrarily) as the amount of rainfall assumed necessary to produce overland flows of water in this study.

High levels of antecedent soil moisture from prior rainfall events can lead to a situation where the infiltration capacity of the soil is exceeded with subsequent rainfall events. Syed et al. (2003) concluded that the antecedent soil moisture in the upper "few" inches of the surface is essentially "lost" within five days of a rainfall event. A more "conservative" estimate to two successive rainfall events of 0.35 inches or more occurring within three days of each other was selected arbitrarily as a "catalyst" for generating overland flows of water in this study.

Measured physiographic characteristics of the watersheds included hillslope position (upper, middle, and lower), hillslope steepness (to nearest 5 percent) and slope aspect (N, NE, E, etc.). An index integrating slope percent and aspect into values of potential solar beam radiation irradiation (Frank and Lee 1966) was analyzed to determined whether combinations of slope gradient and direction of a slope were related to soil erosion and deposition.

The numbers of trees were tallied on 1/4-acre circular plots (Ffolliott et al. 2008) and the crown closure of trees was measured above each of the plots with a 60° spherical densiometer (Lemmon 1956) to characterize the overstories. Annual production (standing biomass) of herbaceous plants and shrubs in the understories was estimated by the procedure outlined originally by Pechanec and Pickford (1937).

RESULTS AND DISCUSSION

Pre-Fire

There were no (statistically significant) differences in either soil erosion or deposition on the Cascabel Watersheds throughout the pre-fire period of the study. Therefore, these respective data sets were pooled for analysis of the pre-fire movement of soil on the watersheds.

Soil erosion and deposition measurements in the spring and fall were compared to determine whether seasonal differences in soil movement occurred. It was found that the spring measurements of soil erosion averaging 15.7 tons/acre were (statistically) similar to the 13.4 tons/acre average of the fall measurements. Seasonal depositions of soil differed, however, with the spring measurements averaging of 4.6 tons/acre less than the fall measurements of 7.9 tons/acre. Examination of the data sets indicated that this difference in soil deposition was attributed primarily to the measurements obtained in 2006. Depositions of soil in the spring of 2006 averaged 3.0 tons/acre, while the average of the fall measurements was 9.0 tons/acre. These "large" differences might have been a result of the "large" differences in seasonal rainfall amounts before the measurements were taken. Measurements of soil deposition obtained in the spring of 2006 followed winter rains totaling only 1.6 inches, while those in the fall were obtained after 15.5 inches of summer rainfall. These respective seasonal rainfall totals represented the extremes in the seasonal totals of rainfall for any year in the pre-fire period of measurements.

There were no consistent patterns in the seasonal magnitudes of soil erosion and deposition relative to rainfall amounts, rainfall intensities, rain amounts necessary to generate overland flows of water, or sequencing of the rainfall events. It could be that the values selected from the literature for these "characterizations" of rainfall did not adequately reflect the on-site conditions on the Cascabel Watersheds. Other (unknown) values might have been more appropriate.

There was a significant relationship between soil erosion and deposition and hillslope position. Soil erosion was generally less on the upper slopes, averaging 9.8 tons/acre, than on either the middle or lower slopes averaging 16.0 and 17.1 tons/acre, respectively. This finding could be attributed to the possibility of "thinner soil profiles" on the upper slopes. However, measurements of soil depths on the hillslopes of the Cascabel Watersheds are not available to confirm this possibility. That deposition of soil is often larger on the lower slopes (Rich 1962, Ruhe and Walker 1968) was corroborated by the pre-fire measurements on the watersheds. Seasonal depositions of soil on the lower slopes of the Cascabel Watersheds averaged 8.5 tons/acre in comparison to average depositions of 5.4 tons/acre on the upper and middle slopes combined. Seasonal soil erosion was also greater on slopes in excess of 25 percent, averaging 19.4 tons/acre, than on the lesser slopes averaging of 11.8 tons/acre. However, seasonal depositions of soil on the watersheds were not related to slope steepness. It was unclear why the measured soil movement was greater on northwardly facing aspects than southwardly facing aspects. Parenthetically, there were no significant differences in the densities of trees or production of herbaceous plants on these two general aspects.

Relationships between either seasonal soil erosion or seasonal depositions of soil and the densities of the tree overstories or the production of herbaceous plants and shrubs in the understories were insignificant or had little predictive value.

Post-Fire

Determining the effects of the prescribed burning treatments and wildfire on soil erosion and deposition on the hillslopes of the Cascabel Watersheds was the second part of this study. Comparisons of the post-fire data sets obtained to date showed that there were no significant differences in soil erosion or depositions of soil on the respective watersheds experiencing either the prescribed burning treatments or wildfire. Therefore, the data sets for these respective watersheds were pooled for comparisons with pre-fire values.

There was a difference between the pre- and post-fire estimates of soil erosion on the watersheds that were burned in the cool-season based on the measurements obtained in the spring of 2008, approximately two months following the prescribed burn. Soil erosion on these watersheds averaged 13.4 tons/acre before the burn, while the measurement of soil erosion obtained shortly after the burn was 21.8 tons/acre. However, this initial increase in post-fire soil erosion was short-lived. Measurements of soil erosion following the summer rains of 2008 and those obtained in 2009 were similar to the pre-fire average. A measurement of the deposition of soil on these watersheds in the spring of 2008 was similar to the pre-fire average.

Post-fire soil erosion and deposition in the fall of 2008 and spring and fall of 2009 were similar to the corresponding pre-fire averages in most instances. More specifically, measurements of soil erosion following the two prescribed burning events were within the range of pre-fire values. Absence of widespread water repellent soils after the events (Stropki et al. 2009), and, as a consequence, the likelihood of a little change in the overland flows of water necessary to transport soil particles downslope were the presumed causes for the lack of significant differences in pre- and post-fire soil erosion rates.

Measurements of soil deposition on the watersheds burned by the prescribed treatments were within the range of pre-fire averages. However, there was a difference in the depositions of soil on the watersheds burned by the wildfire in the fall of 2008 relative to the pre-fire average. Soil deposition on these watersheds before the wildfire averaged 5.8 tons/acre, while the deposition of soil measured in the fall of 2008 was 7.6 tons/acre. The reason for this initial difference in soil deposition is not known. Measurements of soil deposition on these watersheds obtained in 2009 were similar to the average of depositions of soil on the watersheds before the wildfire.Soil erosion and deposition following the burning events were not related to the rainfall after these events, physiographic characteristics of the watersheds, or post-burn vegetation on the watersheds.

CONCLUSIONS

The results of this study should be helpful to land managers and other stakeholders interested in re-introducing more natural fire regimes into the oak savannas of the Southwestern Borderlands region. While the three burning events on the Cascabel Watersheds should be considered case studies, a conclusion that the low severity prescribed burning treatments and wildfire impacting the watersheds had relatively little effect to date on soil erosion and deposition in oak savannas in the region appears warranted. It should be remembered, however, that this conclusion is based on measurements of pre- and post-fire soil movement that were made in a period of prolonged drought.

Knowledge of the effects of prescribed burning treatments of other (higher) severities, in other seasons, and on the array of ecosystem resources and factors affecting the hydrologic functioning of oak savannas is necessary before comprehensive, ecosystem-based plans for introducing more natural fire regimes through prescribed burning treatments.

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