HILLSLOPE SOIL MOVEMENT IN THE OAK SAVANNAS OF THE SOUTHWESTERN BORDERLANDS REGION

by

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ABSTRACT

Oak woodlands and savannas comprise more than 31,000 square miles (80,290 square kilometers) in the southwestern United States and northern Mexico and provide various resources including forage for livestock, wildlife habitat, fuelwood, and recreational areas. Increased woody-plant encroachment into the more open savanna ecosystems has presented a problem to managers and ranchers concerned with maintaining these ecosystems with less overstory density. Prescribed fire has been proposed as a managerial tool to help control woody-plant encroachment and improve the production of forage. Concerns over the ramifications to other ecosystem attributes from the reintroduction of fire, however, have been raised. One concern is how soil erosion rates might be affected. This study examined erosion and deposition rates on a biannual basis for 12 watersheds in the oak savannas of the Southwestern Borderlands Region to provide an indication of soil movement on hillslopes to managers of these ecosystems. Rates were measured at the plot level and compared to plot characteristics before the watersheds were subjected to cool and warm season burns and an unplanned wildfire. Pre-treatment erosion and deposition rates, as well as the initial post-fire erosion and deposition rates after the burns, are reported in this study.

INTRODUCTION

Oak woodlands and savannas comprise more than 31,000 square miles (80,290 square kilometers) in the southwestern United States and northern Mexico (Gottfried et al. 2007). These ecosystems range in elevation between approximately 3,900 and 7,200 feet (1,189 and 2,195 meters) (Gottfried et al. 2000), with oak savannas found at drier and lower elevations that intermingle with desert grasslands and at higher altitudes where oak woodlands merge with oak-pine and pine forests (McPherson 1992). In addition to differences in elevation, distinctions between oak woodlands and oak savannas are related to tree density, with oak savannas characteristically having less canopy closure (Ffolliott et al. 2008). The degree of openness on these landscapes is a function of soil properties, site characteristics, climate, and land use history (Ffolliott 1999). The disparities in resource availability between oak woodlands and oak savannas necessitate that different managerial practices be used.

Oak savannas provide forage for livestock, wildlife habitat, fuelwood for local use, and recreational areas (Ffolliott 1999). Historically, grazing was mostly concentrated in semi-desert grasslands; however, increased settlement and improved water stocking in the early 1900s allowed grazing to expand into the oak ecosystems (McClaran et al. 1992). It was estimated that 75 percent of oak savannas in the southwestern United States were being grazed in 1997, although that amount has diminished in recent years (McPherson 1997). Use in Arizona was even higher, with as much as 85 percent of the 1.1 million acres (445,344 ha) of oak ecosystems used by livestock in 1992 (McClaran et al. 1992). The majority of this land was in federal management.

Despite the increased use of oak savannas, however, these ecosystems remain poorly understood (Ffolliott et al. 1992; Gottfried et al. 2000). Over-utilization of ecosystem resources, fragmentation from increased human development, and alteration of fire regimes could negatively impact how these systems function. Encroachment by woody species such as mesquite (*Prosopis* spp) and higher densities of the oaks themselves, along with reduced forage for livestock grazing, are some of the concerns related to the management of these areas.

Efforts to more effectively manage southwestern oak savannas, among other ecosystems in the region, were intensified in 1994 by the U.S. Forest Service as part of the Southwest Borderlands Ecosystem Management Project (Gottfried and Edminster 2005). The Rocky Mountain Research Station, National Forest system management, local stakeholders, universities, and other state and federal agencies were brought together with the mission of developing and implementing a comprehensive ecosystem management plan. This plan would be aimed at restoring natural processes and enhancing productivity and biological diversity of selected ecosystems, while also ensuring a viable rural economy and social structure (DeBano and Ffolliott 2005; Gottfried and Edminster 2005). Existing information on the functions of ecosystems in the area was to be synthesized by participating groups, future research needs identified, and information disseminated to managers and other stakeholders for the purposes of improved land stewardship in the Madrean Archipelago region. One of the identified research needs was to examine the effects of reintroducing fire into the border landscapes including the oak ecosystems (Gottfried and Edminster 2005; Gottfried et al. 2005).

Historically, fire in the region is believed to have occurred in late spring or early summer prior to the monsoon season when conditions were dry (Swetnam 2005). While reintroduction of prescribed fire under similar "warm season" conditions might mimic natural fire regimes of the past, concerns over the severity of fire impacts on vegetation, threatened or endangered species, or other ecosystem components led to considerations for less extreme burning conditions during the "cool season." Several prescribed fires were ignited in the late 1990s and early 2000s including the 6,000 acre (2,429 ha) Baker Canyon Fire (1995), the 12,000 acre (4,858 ha) Maverick Fire (1997), the 43,000 acre (17,409 ha) Baker II Fire (2003) (Allen 2006), and the Cottonwood Fire (2007). Some of the reasons for reintroducing fire to the region included reducing invasive trees and shrubs, lessening tree cover, and creating a mosaic of trees and grass (Clark 1999; Gottfried and Edminster 2005). One of the shortcomings to initiating these prescribed fires, however, was that more comprehensive pre-fire measurements and post-fire monitoring and evaluation of the fires' effects on watershed attributes had not been conducted. One attribute of concern was the effects of fire on hillslope soil movement.

The purpose of this study was to examine the rates and factors influencing hillslope soil movement (erosion and deposition) in oak savannas prior to cool and warm season prescribed burns. An unexpected wildfire provided another study element. This thesis also presents initial estimates of soil movement rates on hillslopes after the fire events. Prior to the presentation of the study details and results, background information on oak ecosystems and hillslope soil movement in the region is provided.

PERSPECTIVES TO STUDY

OAK ECOSYSTEMS

The Southwest Borderlands project area encompasses approximately 800,000 acres (323,887 ha) (Gottfried et al. 2005). The project area includes southwestern New Mexico and southeastern Arizona, although northeastern Sonora and northwestern Chihuahua share similar ecosystem resources. Variations in physiographic characteristics such as lower valley desert grasslands and higher elevation mountain islands has led to rich biological diversity including more than 1,000 native plant species on some mountain ranges (Gottfried and Edminster 2005). A large component of the region is composed of oak ecosystems including woodlands and savannas.

Distinctions between oak woodlands and savannas have not always been made in studies of these ecosystems. Recent research has shown, however, that differences do exist and considerations of these differences can be important for managerial purposes (Ffolliott et al. 2008). Density of tree overstory is one of the main attributes used for differentiating oak woodlands and oak savannas. The more open compositions of southwestern oak savannas generally occur at lower elevations than the more dense oak woodlands and are recognized as transitional ecotones between woodlands and desert grasslands (Felger and Johnson 1994). Changes in vegetation structure and productivity along these elevation gradients, including increased biomass in oak woodlands compared to savannas, are governed by a rise in precipitation at higher elevations as described by Whittaker and Niering (1975) and others. Upper oak communities examined by these authors had limited undergrowth and herbaceous cover, while an open oak woodland located at lower elevations had approximately 8 percent canopy coverage and moderate herbaceous cover. The lower oak community could be termed an oak savanna under the criteria outlined by McPherson (1997) and others as having less than 30 percent woody plant overstory and the presence of a graminoid understory.

In addition to moisture availability, discrepancies in tree density and herbaceous understory between oak woodlands and savannas might be a reflection of ecosystem disturbances. As Bahre (1991) explains, oak range in southeastern Arizona is roughly the same as it was in the late 1800s despite the cutting of oaks for mines, fuelwood, and other purposes. Densities and stand structures, however, are probably different because of fire suppression, grazing, and coppicing. Competition between overstory and understory as well as recovery after disturbances such as coppicing and fire has been examined further by Borelli et al. (1994), Weltzin and McPherson (1994), Ffolliott and Bennett (1996), McPherson and Weltzin (1998), Ffolliott and Gottfried (2005), and others.

HILLSLOPE SOIL MOVEMENT

Soil movement is distinguished by erosion (soil loss), deposition (soil accumulation), and equilibrium (the absence of soil movement or equal amounts of erosion and deposition over the same period) for the purposes of this study.

Soil Movement Processes

Soil is composed of mineral and organic matter, air, and water (Hendricks 1985). In addition to providing a medium for growth, it contains nutrients for plant metabolism and growth, and influences rates of infiltration and runoff (Buol et al. 2003). Increased volume and velocity of surface runoff due to limited infiltration is associated with increased rates of soil erosion, which can be costly both ecologically and economically. Therefore, an understanding of the factors that contribute to minimal infiltration and increased surface runoff is crucial to land managers.

Soil erosion caused by water is typified by three major processes including sheet erosion, rill erosion, and gully formation (Brooks et al. 2003). Sheet erosion is a process in which entrainment of soil particles on slopes is mostly uniform across the soil surface (DeBano et al. 2005). Concentration of sheet erosion can lead to rill formation that appears as small distinct channels and accounts for the greatest amount of soil loss worldwide (Brooks et al. 2003). If the erosive process is further intensified, the convergence of rills can develop into deep gullies that are capable of removing large quantities of soil over short periods of time (Bull 1997). Dry ravel or large mass failures can also contribute to soil loss on steeper slopes, especially after disturbances (DeBano et al. 1998; Brooks et al. 2003). Sheet erosion and possibly some rill erosion are the processes examined in this study.

Influence of Precipitation

Sites that are most vulnerable to soil erosion are those with low permeability, steep slopes, and/or denuded vegetation (Brooks et al. 2003). Low permeability in soils can be caused by several factors of which raindrop impact, shallow lithic content or fine textured horizons, and over-saturation are a few. Unobstructed raindrops can break down soil structure and redistribute fine soil material across the soil surface, which effectively clogs pores and restricts infiltration (Brooks et al. 2003). High levels of antecedent soil moisture from previous precipitation events or high precipitation intensity are additional factors that can contribute to infiltration capacity being exceeded with subsequent surface runoff and resulting soil detachment.

Influence of Physiography

The runoff of water created by low soil permeability is capable of detaching and transporting particles from the soil surface (Brooks et al. 2003; Paige et al. 2003). Small soil particles are more easily entrained in surface runoff, but steeper slopes can accelerate runoff velocity which (in turn) can generate more force for moving larger particles and greater amounts of soil (Brooks et al. 2003). Steeper slopes generally occur at middle hillslope positions compared to upper hillslope positions. Greater soil loss might be expected at the middle hillslope, while lower hillslope positions are often areas of deposition (Ruhe and Walker 1968). The aspect at which hillslopes face can affect vegetation cover, soil moisture, and freezing and thawing, each of which might also alter soil movement processes. Factors such as vegetation and soil moisture could influence overland flow rates or while freeze and thawing processes could loosen soil particles and predispose them to entrainment by subsequent overland flow events.

Influence of Vegetation

Vegetative cover can aid in ameliorating erosive processes at several scales, including above and below the surface of the ground, and depending on the horizontal connectivity, at the micro-topographic and landscape scale. Herbaceous plants, including grasses and forbs, can diminish soil erosion by reducing raindrop impact through interception, enhancing infiltration by loosening soils (Fielder et al. 2002), slowing runoff by creating roughness or drag (Wainwright et al. 2000), and holding soil with roots (Clary and Kinney 2002; Baets et al. 2006). Grasses and other vegetation can counteract the influence of slope and low soil permeability on both a small and large scale. Grass clumps or patches at a small scale increase soil permeability by breaking up soil with their roots and, thus, raise infiltration capacity (Fielder et al. 2002; Baets et al. 2006). Grass clumps can also cause meandering of overland flow, essentially slowing runoff down further (Tongway and Ludwig 1997; Fielder et al. 2002). Viewed on a larger scale, the patchiness of grasses can mitigate runoff velocities by increasing roughness or acting as obstructions to effectively cut off fetch along slopes (Tongway and Ludwig 1997; Tucker 1997; Wilcox et al. 2003; Baets et al. 2006).

Influence of Fire

Loss of organic matter in upper soil layers by burning is responsible for breaking down soil structure, which is the greatest impact a fire can have on soil (DeBano et al. 1998). Soil structure in upper soil layers of a profile is primarily a result of the aggregation of mineral particles by organic matter. Greater amounts of organic matter tend to have lower bulk densities and more pore space, both of which improve infiltration capacity. Therefore, burning of organic matter reduces structure and collapses pore space, making soil more susceptible to runoff and soil erosion, particularly in the form of dry ravel and rill erosion.

An additional concern of reduced soil structure after a fire is whether a higher severity burn creates a water repellent layer in the soil. Fire-induced water repellency is the product of volatilized organic compounds being precipitated downward into the soil surface by the heat of a fire before cooling and condensing into a less permeable layer (DeBano 2000). A water repellent layer can be of variable thickness and continuity across a landscape, with the consequence being increased pore pressure as the layer above the repellent layer becomes oversaturated during precipitation events. Reduced shear stress ensues until soil slippage and entrainment of soil begins. The increase of surface runoff and soil erosion resulting from water repellency and reduced canopy cover can persist for variable amounts of time after a fire. Methods used classify water repellency levels based on the number of seconds needed for a drop of water to penetrate the soil surface have been outlined by Clark (2001). For example, a drop that penetrates the soil surface in less than 10 seconds would fall under the category of slight repellency, whereas a drop that persists for more than 40 seconds exhibits strong repellency.

Hillslope Soil Movement Rates

Ascertaining rates of hillslope soil movement in southwestern oak savannas can be challenging even if potentially controlling factors such as herbaceous cover, ground cover, tree overstory, slope, soil texture, burn intensity, and time are known. Added to the difficulty is the possibility that the variable effects reported in other studies might result from the time of year measurements were taken or monitoring methods employed (Emmerich and Cox 1994). For example, studies aimed at examining the differences in soil erosion rates after fires that have been conducted at varying post-fire intervals can be difficult to compare due to differences in seasonal precipitation or the stage of plant recovery. The scale at which measurements are conducted can also lead to discrepancies in the rates at which soil movement is described (Osterkamp and Toy 1997; Wilcox et al. 2003; Boix-Fayos et al. 2006; Nichols 2006). In spite of these complications, however, a few studies have been conducted to assist in estimating pre- and post-fire erosion rates for oak savannas.

Soils in oak ecosystems for southeastern Arizona are typified as shallow and rocky (McPherson 1997) with moderately fine to moderately coarse textures (Lopes and Ffolliott 1992). Infiltration and percolation are often impeded by shallow lithic contact causing an uneven distribution of runoff. The variations in surface runoff can cause a heterogeneous redistribution of water, nutrients, and soil leading to a mosaic vegetative pattern. Moir (1979) attempted to relate vegetative patterns to soils and erosive processes on a large scale for the central Peloncillo Mountains in New Mexico. He reported that oak savannas were generally found at the uppermost slopes of broad alluvial mountain fronts that were characterized by cobbly and coarse gravelly surface textures.

Moir et al. (2000) evaluated soil redistribution as related to vegetative cover at 19.7 inch (0.5 m) intervals along a total of 10 transects at four sites in the same area as studied earlier by Moir (1979). Despite finding a reduction in vegetation cover between the initial and subsequent measurements, an overall average increase in soil deposition of 0.032 in/yr (0.8 mm/yr) was found across the four study locations, indicating that vegetation cover alone might not be a controlling factor with respect to soil being removed or deposited on a site. However, the small number of vegetation sample sizes and infrequency of measurements might limit inferences into the associated effects of herbaceous cover on erosion estimates. Average annual erosion rates were as high as 0.055 in/yr (1.4 mm/yr) with the highest rates of soil loss found on steep, south-facing hillslopes. The authors noted that the high rates might have been enhanced by gully systems and a "single intense rainfall" totaling 4.1 inches (103 mm) on June 30, 1981.

Distinctions between plant cover types (that is, shrubs versus grasses) were not made by Moir et al. (2000), but they might be of importance as evidenced in studies that have found soil movement differs depending on whether cover is dominated by shrubs or grasses (Abrahams et al. 1995; Parsons et al. 1996; Wainwright et al. 2000; Nearing et al. 2005). For example, Nearing et al. (2005) found that sites in southeastern Arizona with greater grass cover obstructed runoff and lessened erosion rates compared to shrub dominated sites. Whereas shrub covered sites with approximately 25 percent canopy cover averaged 2.27 tons/ac/yr (5.08 Mg/ha/yr) erosion, grass covered areas with approximately 35 percent canopy cover only lost 1.30 tons/ac/yr (2.91 Mg/ha/yr).

A reduction in vegetative cover could have an even more pronounced effect on erosion than changes in vegetation type. Paige et al. (2003) examined surface runoff rates and soil movement on a site that included oak savannas and pine-oak woodlands one month after the Ryan Wildfire in 2002 in southeastern Arizona. These authors used rainfall simulators on burned and unburned sites with both sandy gravelly loam soils and clay loam soils. They found that the increases in the surface-runoff ratios (Runoff ÷ Precipitation applied) and sediment yield ratios (Sediment Yield ÷ [Runoff x Slope of plot]) were related to reduced ground and canopy cover. It was determined that the surface-runoff ratio on burned areas was 74 percent greater than on the unburned areas for the sandy gravelly loam soils. On the clay loam soils the increase was only 5 percent more for the burned plots. Sediment yield ratios showed greater increases on the burned versus the unburned plots. There was a 2,230 percent and 399 percent increase on the sandy gravelly loam and clay loam soils, respectively, where organic cover had been removed by the fire versus sites where organic cover had not been affected. Sediment yields were provided by the authors, but it should be noted that these rates were indicative of single simulated rainfall events with intensities aimed at generating runoff. Sediment yields on the sandy gravelly loam soils ranged from 0.04 tons/ac (0.09 Mg/ha) to 0.05 tons/ac (0.11 Mg/ha) on unburned sites and increased to 1.13 tons/ac (2.53 Mg/ha) to 1.43 tons/ac (3.20 Mg/ha) on burned sites. Rates for the clay loam soils ranged from 0.28 tons/ac (0.63 Mg/ha) to 1.33 tons/ac (2.98 Mg/ha) on unburned sites and from 2.49 tons/ac (5.58 Mg/ha) to 2.90 tons/ac (6.50 Mg/ha) on burned sites.

The presence or absence of vegetation alone might not fully explain soil movement rates. As (Ritchie et al. (2005) found on a shrub site at the Lucky Hills Watershed in southeastern Arizona, a greater presence of rock fragments in the soil surface resulted in reduced soil erosion rates, whereas the presence of vegetative cover did not play a significant role. On sites with less than 40 percent rock fragments, erosion rates averaged 2.23 tons/ac/yr (5.0 Mg/ha/yr), while sites with greater than 40 percent rock fragments only averaged 0.71 tons/ac/yr (1.6 Mg/ha/yr). It has also been hypothesized that the armoring of the soil surface by rock fragments reduced the incidence of soil loss on sites subjected to multiple burns (Robinett and Barker 1996). It is conceivable, therefore, that even with reduced vegetative cover after a disturbance such as fire, soil movement rates might not be significantly altered if the soil surface is armored by coarse soil textures. A more thorough examination of erosion processes in these ecosystems would be useful to managers of these landscapes, especially if disturbances such as prescribed fire are to be introduced.

DISCRIPTION OF STUDY

OBJECTIVES

In an effort to understand the ecosystem resources and functions of oak savanna watersheds as part of the Southwest Borderlands Ecosystem Management Project, a set of 12 watersheds were located on the eastern side of the Peloncillo Mountains in southwestern New Mexico (Gottfried et al. 2005). The purpose of the study on these watersheds was to examine ecosystem resources and functions such as forage production, hillslope soil movement, hydrology, sedimentation, tree overstory characteristics, surface runoff, and wildlife prior to and after exposure to cool and warm season prescribed burns on the watersheds. The first objective of the study reported in this thesis was to present the pre-fire hillslope soil movement rates for the study area and the possible contributing factors. A second objective was to provide an initial estimate of soil movement after cool and warm season burns, and an unplanned wildfire on the watersheds.

STUDY AREA

The Cascabel Watersheds, the study area, lie between 5,380 and 5,590 feet (1,640 and 2,195 m) in elevation, approximately 31 miles (50 km) south of the town of Animas, New Mexico, on the eastern piedmont of the Peloncillo Mountains. Within the Coronado National Forest, these watersheds vary between 19 and 59 acres (7.7 and 23.9 ha) for a combined area of 451 acres (182.6 ha) (Gottfried et al. 2006). Straddled along a ridgeline that generally runs from east to west, six of the watersheds drain towards Walnut Creek to the north, while the surface runoff from the south-facing watersheds flows into Whitmire Creek. A map of the watersheds is presented in Figure 1.

Climate

There is a bimodal precipitation regime in the southwestern United States where the study was conducted. The first precipitation period is the monsoon period, which occurs from July through September and can account for about half of the annual precipitation (Sheppard et al. 2002). Storms in this period are characterized by convective thunderstorms that can provide intense rainfall over small variable spatial extents. Gottfried et al. 2006 described one particular storm during August of 2005 for the Cascabel study area in which nearly three inches of precipitation fell over a period of

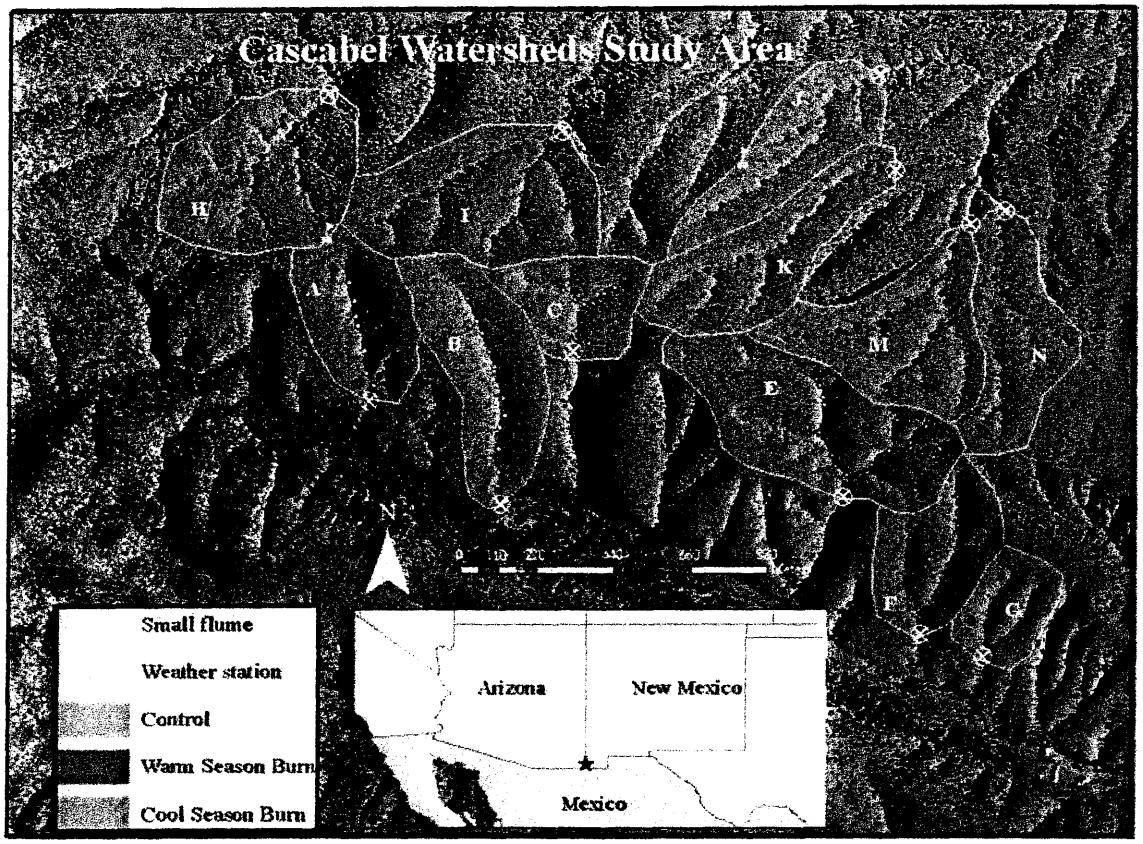

Figure 1. Location of the Cascabel Watersheds within the Coronado National Forest in southwestern New Mexico. Watersheds A-G drain south towards Whitmire Creek while watersheds H-N flow north to Walnut Creek. Watersheds are highlighted according to the original study plan before an unplanned wildfire. The four controls and Watershed I were subsequently categorized as having undergone wildfire burn treatments. Map courtesy of Karen A. Koestner.

a few hours and lead to peak flows exceeding 50 ft^3/sec on at least two watersheds. The second precipitation period occurs between November and April and is distinguished by more widespread frontal storms that are less intense and of longer duration.

The nearest long-term precipitation gauge to the study area at the Diamond A Ranch indicated an annual average of 21.8 ± 1.2 inches (55.4 ± 3.1 cm) (Ffolliott et al. 2008). A five-year average at a weather station located on the study site during 2002-2006 showed precipitation to be 16.0 ± 2.8 inches (40.6 ± 7.1 cm) per year (Gottfried et al. 2007). This lower average precipitation is indicative of several years of drought conditions affecting the region. The average precipitation by month during the pre-treatment period (before fire) is presented in Figure 2.

Geology

Bedrock geology on the watersheds consists largely of rhyolite lava flows covered by volcaniclastic sedimentary rocks. The boundary between the rhyolite and the overlying sedimentary rocks is described as "sharp" suggesting that the lava flow was probably inundated quickly (Youberg and Ferguson 2001). Three sedimentary layers are defined above the lava layers — a lower boulder-cobble conglomerate, a middle pebbly sandstone, and a cobble-pebble conglomerate on top. Residual outcroppings of these layers are found on the study site.

Quaternary surface geology includes alluvial deposits found in channels or on fans. Two alluvial sources are from Whitmire Creek and older piedmont deposits from within the Cascabel Watersheds (Youberg and Ferguson 2001). The former deposits are

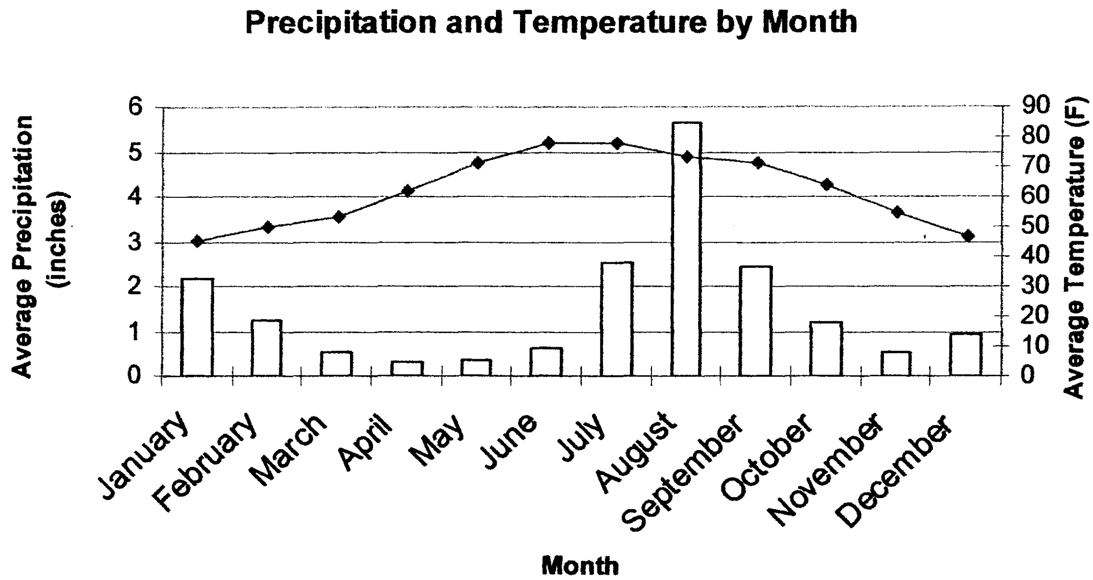

Figure 2. Average pre-treatment precipitation at the Cascabel Watersheds by month (June 2004—August 2007) is shown by bars. Average monthly temperature in degrees Fahrenheit is shown by the dots connected by the blue line for the same time period. Data was collected from weather stations located near watersheds J2 and H.

evident as floodplain or terrace deposits, while the latter are small channel bars or terraces that are more noticeable at channel confluences. Hillslopes and ridges on the watersheds are composed of both colluvial and residual soils.

Soils

Four major soil classifications of the Cascabel Watersheds were identified by Robertson et al. (2002). Three of the four classifications are confined to relatively small sections on the western end of the study area. The majority of the soil is described as Lithic Argiustolls with some variations in the particle size class distributions. Lithic Ustorthents, Typic Ustorthents, and Lithic Haplustolls make up the remaining area. The lithic designation given to some of the soil classifications is indicative of a shallow boundary between the soil surface and an underlying mostly continuous coherent material (Soil Survey Staff 2006). This shallow contact led Robertson et al. (2002) to estimate surface runoff to be high or very high for all sections of the study area.

Soil textures on site are almost exclusively sandy loams and described as skeletal meaning that rock fragments such as gravel or cobble are equal to or exceed 35 percent of the soil volume (Robertson et al. 2002). Additional commonalities among the soils classified are an ustic soil moisture regime and mesic soil temperature regime. This signifies that mean annual temperature of soil ranges between 47° F (8° C) to 59° F (15° C) with limited moisture availability for plants except during times of the year when temperatures are optimal for plant growth (Soil Survey Staff 2006).

Vegetation

Tree overstory inventories on the Cascabel Watersheds have indicated the dominant tree species to be Emory (*Quercus emoryi*), Arizona white (*Q. arizonica*), and Toumey oak (*Q. toumeyi*), as well as alligator juniper (*Juniperus deppeana*) (Ffolliott and Gottfried 2005). Emory oak is the most frequently encountered species, representing about 60 percent of all trees tallied (Ffolliott et al. 2008). Redberry juniper (*J. coahuilensis*), pinyon (*Pinus dicolor*), and mesquite (*Prosopis velutina*) are also found on the watersheds.

Differentiation between overstory densities in oak ecosystems of the Southwest is addressed by Ffolliott et al. (2008). The authors suggest that differences in average overstory density between the oak savannas at the Cascabel Watersheds and oak woodlands on a south-facing slope in the Huachuca Mountains might necessitate site-specific managerial practices. Average tree densities of medium and large trees with diameter root collar ≥ 5 inches (12.7 cm) were significantly less at the oak savannas of the Cascabel site than at the oak woodland site in the Huachuca Mountains. The density of saplings with diameter root collar from 1 to 5 inches (2.5 to 12.7 cm) at each site was statistically similar, while the overall average density of trees per acre was less at Cascabel. Tree density on the Cascabel Watersheds is about 90 trees/ac (36.4 trees/ha).

Herbaceous species on the Cascabel Watersheds are predominantly grasses, with forbs making up a smaller component of the herbaceous understory (Ffolliott et al. 2008). Common grass species are blue (*Bouteloua gracilis*), sideoats (*B. curipendula*), slender (*B. repens*), and hairy (*B. hirsute*) grama, bullgrass (*Muhlenbergia emersleyi*), common wolfstail (*Lycurus phleoides*), and Texas bluestem (*Schizachyrium cirratum*) (Ffolliott and Gottfried 2005; Ffolliott et al. 2006). Shrubs include beargrass (*Nolina microcarpa*), fairyduster (*Calliandra eriophylla*), common sotol (*Dasylirion wheeleri*), Fendler's ceanothus (*Ceanothus fendleri*), Mexican cliffrose (*Purshia mexicana*), and pointleaf manzanita (*Arctostaphylos pungens*).

FIELD METHODS

Sample Design

A total of 422 sample points were established on the Cascabel Watersheds to measure ecosystem and hydrologic resources. Location of the plots was based on a systematic sampling design with multiple random starts (Shiue 1960). Sample points were located along transects that ran perpendicular to channels from ridge to ridge with the aim being to maximize variability between plots along gradients and minimize variability between transects. The distance between plots differed by watershed depending on the area of the watersheds being measured. The number of sample points varied between 31 and 42 for each of the 12 watersheds. The minimum interval between sample points was 70 feet (21.4 m) and the maximum 240 feet (73.2 m). Ecosystem and hydrologic resources measured for this study (at every third plot) included hillslope soil movement, physiographic hillslope characteristics (hillslope position, slope percent, aspect, slope-aspect interaction), herbage production, overstory densities, and canopy closure of trees. The total number of plots, interval distance between them, and related information for each watershed is presented in Table 1.

Table 1. Characteristics of the Cascabel Watersheds and sample plots.

Watershed	Acres	Hectares	Erosion Plots	Total erosion pins	Erosion plot interval on transects (ft)	Erosion plot interval on transects (m)
A	31.5	12.8	12	36	360	109.8
B	38.8	15.7	12	36	270	82.3
C	27.9	11.3	11	33	480	146.4
Eb	59.3	24.0	14	42	720	219.6
F	32.3	13.1	11	33	360	109.8
G	18.8	7.6	13	39	255	77.8
H	48.5	19.6	12	36	450	137.2
I	52.4	21.2	12	36	480	146.4
J2	31	12.6	11	33	240	73.2
K	41.1	16.6	13	39	240	73.2
M	41.8	16.9	12	36	330	100.6
N	29.6	12.0	13	39	210	64.0
Total	453	183.4	146	438		

Soil Erosion Measurements

At every third plot, starting with the first plot on each watershed, three erosion pins, three inches (7.62 cm) in length, were driven into the ground until the top of each pin was flush with the soil surface. The pins were six feet (1.83 m) from the plot center with two pins upslope and the third pin downslope. There were a total of 438 pins for all of the watersheds with a minimum of 33 and a maximum of 42 pins on individual watersheds (Table 1). Measurements of the amount of soil eroded from below or deposited above the cap of each pin were made after the winter and summer precipitation periods. All pins were re-set after each season of measurements. The first measurements were completed in October of 2004 after the summer monsoons and have continued to be taken biannually since that time. A bulk density value of 70.51 lb/ft^3 (1.13 g/cm^3) for soils on the watersheds was used to calculate the average soil loss in tons/ac (Mg/ha).

Precipitation

Precipitation amounts recorded at two weather stations on the Cascabel Watersheds were used to average seasonal precipitation amounts for each measurement period. One of the weather stations was located on watershed H on the western side of the study area and the other was more centrally located at watershed J2 (Figure 1). Threshold precipitation events, recurring storms, precipitation intensity, and average storm durations were also measured for the purpose of helping to explain differences between hillslope soil movement rates among watersheds and seasons.

Physiography

Information on spatial variability of hillslope erosion and deposition rates as influenced by physiographic characteristics of the plots was examined. Hillslope position was divided into three categories (upper, middle, and lower). Slope steepness was measured to the nearest five percent with a clinometer. Slope aspects were classified into one of nine possible directions (N, NE, E, SE, S, SW, W, NW, and No Aspect) with "No Aspect" referring to plots that were level and not facing any direction. An index accounting for slope percent and aspect interactions developed by Frank and Lee (1966) was used to determine whether an interaction between the gradient and direction a plot faced influenced soil movement. Values from the index were measurements of solar irradiation for a plot measured in Langleys (gram calorie/cm^2) at 32° latitude during the mid-point dates during the erosion measurement periods (that is, July 27 and February 20).

Vegetation

Number of trees in the overstory was measured on ¼ acre (0.10 ha) circular plots centered at each of the sampling points (Ffolliott et al. 2008). Crown closure above each plot was measured with a 60° spherical densiometer as outlined by Lemmon (1956). Production of herbaceous plants and shrubs was estimated by weight-estimate procedures on 9.6 ft^2 (0.89 m^2) circular plots (Pechanec and Pickford 1937). The estimated production of these understory plants at each plot was used as a proxy for plant cover.

ANALYTICAL METHODS

Pin measurements were initially examined for erosion or deposition abnormalities (for example bioturbation) on or near the plot with pins affected removed from the analysis. Pin measurements were subsequently averaged by plots and categorized depending on whether they displayed erosion, deposition, or equilibrium. The distribution of the measurements from the erosion and deposition categories were then examined for skewness and a visual test of normality was conducted using the Kolmogorov-Smirnov test (Sall et al. 2005) to determine whether parametric or non-parametric statistical tests were appropriate. In cases when non-parametric tests were used, average soil movement was compared based upon ranks rather than the specific measured values of erosion or deposition, which precluded the possibility of providing confidence intervals. All statistical comparisons were evaluated at the $\alpha = 0.10$ level of significance.

Soil Movement

Data among the twelve watersheds were pooled before comparing soil erosion and deposition rates by seasons (fall vs. spring) using a Mann-Whitney test. Nemenyi tests—a non-parametric test used to compare means between groups (Zar 1999)—were used to examine whether erosion rates differed by individual measurement periods or years. Plots that displayed equilibrium during a measurement interval were not tested. However, the proportion of equilibrium plots was noted in comparison to those that showed deposition or erosion.

Precipitation

Comparisons of precipitation measurements from the two weather stations were analyzed with a t-test. Averaged precipitation measurements from the gauges were then arbitrarily grouped by measurement period, daily events that were equal to or exceeded 0.35 inches (8.89 mm), hourly intensities that averaged a minimum of 0.25 in/hr (6.35 mm/hr), and successive storms of 0.35 inches (8.89 mm) or greater within three days of each other.

Physiography

Comparisons of soil erosion and deposition rates for the different aspects, five percent slope intervals, and hillslope positions were accomplished using Nemenyi tests. Simple linear regression was used to examine whether a relationship existed between soil movement and a slope-aspect interaction using an index developed by Frank and Lee (1966). The comparisons between physiographic differences were made across all pooled measurement periods.

Vegetation

Simple linear regression was used in three tests in comparing soil movement and vegetation. The first test was undertaken to determine whether relationships existed between soil movement and estimated total herbage production. Secondly, this test was used to determine if hillslope soil movement was related to crown closure percentages.

Simple linear regression was also used to determine if soil movement rates were related to the number of trees per acre. Each test comparing soil movement was examined for measurements combined across all measurement periods.

Post-fire

The second objective of this study was to provide initial estimates of post-fire soil movement rates as stated above. Cool and warm season burns on four watersheds each were intended to be compared to one another and to four remaining unburned control watersheds. The cool season burns were conducted on March 4 and 11, 2008 on Watersheds C, H, K, and N (Figure 1). Warm season burns followed two months later on May 20 for Watersheds A, Eb, and F. On the day after the warm season burns, high winds allowed smoldering fuels to spot into unburned areas. The four control watersheds (B, G, J2, and M) and the remaining unburned Watershed I—intended for a warm season burn—were ignited. The control watersheds were subsequently categorized as wildfire treatments and Watershed I was dropped from the post-fire statistical analysis comparing treatments. Friedman's analysis of variance by ranks was used to compare treatments for fall 2008 erosion and deposition measurements. Mann-Whitney tests were used to compare pre- and post-fire erosion and deposition rates for the specific fire treatments.

RESULTS AND DISCUSSION

PRE-FIRE

Distribution

Examination of erosion pins measured revealed that at least seven were impacted by animals digging on or near the plot. These pins were removed from the analysis along with 19 plots that were missed during a measurement period prior to averaging pin measurements at all plots. After averaging the pins by plot, it was determined that 545 had measurable erosion, 203 deposition, and 255 no net soil gain or loss (Table 2). A distribution of the erosion measurements had a positive skew with a mean of 14.16 tons/ac (31.79 Mg/ha), while the deposition measurements were negatively skewed and averaged 6.30 tons/ac (14.11 Mg/ha). Neither distribution was normally distributed. Transformations of the erosion and deposition distributions were unsuccessful and, therefore, non-parametric tests were employed except when simple linear regression tests could be used. No significant differences were found between erosion or deposition across the 12 watersheds and, therefore, pin measurements were pooled.

Soil Movement Rates

Since measurement periods were reflective of the bi-modal precipitation regimes in the region, soil erosion and deposition rates from the fall measurement periods—occurring after the summer monsoons—were compared to the spring measurement

Table 2. Proportion of plots where erosion, deposition, or soil equilibrium was measured. Counts are on top with the percentage of the total count for that specific measurement period in parenthesis below.

Measurement Period	Erosion	Deposition	Equilibrium	Count Total
Fall 2004	102	20	21	143
	(71)	(14)	(15)	
Spring 2005	101	19	25	145
	(70)	(13)	(17)	
Fall 2005	82	29	32	143
	(57)	(20)	(22)	
Spring 2006	4	32	104	140
	(3)	(23)	(74)	
Fall 2006	85	37	20	142
	(60)	(26)	(14)	
Spring 2007	77	46	21	144
	(53)	(32)	(15)	
Fall 2007	94	20	32	146
	(64)	(14)	(22)	
Overall Pretreatment Total	545 (54)	203 (20)	255 (25)	1003

periods—representing winter precipitation—to determine whether statistical differences existed. Fall soil erosion estimates of 13.40 tons/ac (30.02 Mg/ha), were not found to significantly differ from spring measurements that averaged 15.67 tons/ac (35.10 Mg/ha). However, seasonal deposition rates did significantly differ, with fall estimations of 7.86 tons/ac (17.61 Mg/ha) exceeding spring estimates of 4.58 tons/ac (10.26 Mg/ha). Closer examination showed that seasonal deposition differed in 2006, but not in 2005 or 2007. Fall deposition rates in 2006 of 9.02 tons/ac (20.21 Mg/ha)—the second largest amount for any pretreatment period—were greater than spring rates of 2.97 tons/ac (6.65 Mg/ha), which amounted to the least deposition of soil of any pretreatment period. Differences in deposition between these two seasons could have been the result of differing precipitation amounts. Spring deposition measurements for 2006 received 1.65 inches (4.19 cm) of winter precipitation, while in the fall of that same year 15.46 inches (39.27 cm) of monsoon period precipitation was recorded; the least and most pretreatment precipitation amounts respectively.

Combining seasonal soil movement amounts across years revealed that erosion in 2005, which averaged 27.56 tons/ac (61.73 Mg/ha), was significantly greater than soil loss in 2006 and 2007 which averaged 12.54 tons/ac (28.10 Mg/ha) and 12.65 tons/ac (28.33 Mg/ha) respectively. Precipitation amounts in 2005 exceeded amounts during the next two years which might have led to statistically higher erosion during that year. As outlined in the next section, there were also a greater number of large storm events and recurring storms during 2005, including one particularly high intensity thunderstorm on August 23 in which nearly 3 inches (76.2 mm) of precipitation fell on the study area (Gottfried et al. 2006). Deposition rates did not significantly differ between 2005 and

2007. Erosion and deposition rates specific to pretreatment measurement periods and years are presented in Tables 3 and 4, respectively.

Caution should be exerted when comparing these annual soil movement rates to other regional studies for “at least” two reasons. The first is that many studies fail to treat erosion and deposition as two distinct processes (that is, rates are averaged together) and thus erosion and deposition measurements from Cascabel are likely to exceed others. Secondly, extrapolation of smaller scale plot measurements to larger scales can be misleading because soil loss decreases and deposition can increase with the increasing scale on which it was measured as a result of storage on site (Osterkamp and Toy 1997; Wilcox et al. 2003; Boix-Fayos et al. 2006). Basically, sinks of soil deposition are more abundant with increasing scale, which could mean that the soil loss measured on the plots at Cascabel might be overestimated at the acre scale. One important sink is channel bottoms, which are being addressed in a concurrent study by the U.S. Forest Service, and could account for much of the soil removed from the hillslope plots. Despite these concerns, the rates from measurements at Cascabel should not be devalued since changes in magnitude of either soil erosion or deposition can reveal how soil movement might be related to changes in precipitation patterns or plot characteristics. For this reason, the potential influence of precipitation, plot physiography, and vegetative cover on erosion and deposition are examined below.

Table 3. Mean soil erosion in tons/ac and Mg/ha by measurement period and year.

Season	Tons/acre	Mg/ha
Fall 2004	17.94	40.19
Spring 2005	19.55	43.79
Fall 2005	18.14	40.63
Spring 2006	12.59	28.20
Fall 2006	11.84	26.52
Spring 2007	10.73	24.04
Fall 2007	5.84	13.08
Year		
2005	27.56	61.73
2006	12.54	28.09
2007	12.65	28.34

Table 4. Mean soil deposition in tons/ac and Mg/ha by measurement period and year.

Season	Tons/acre	Mg/ha
Fall 2004	15.26	34.18
Spring 2005	5.59	12.52
Fall 2005	4.38	9.81
Spring 2006	2.97	6.65
Fall 2006	9.02	20.21
Spring 2007	5.29	11.85
Fall 2007	3.27	7.33
Year		
2005	8.97	20.09
2006	8.92	19.98
2007	5.49	12.30

Precipitation

Precipitation recorded on the two gauges was not statistically different and, therefore, were averaged and then compiled by each measurement period. The cumulative precipitation for each measurement period did not appear to explain erosion and deposition amounts for the same period as seen in Figures 3 and 4, respectively. Therefore, additional precipitation characteristics were examined to determine if they might have affected soil movement. One characteristic was precipitation events capable of inducing overland flow. To explore the possible effects of precipitation events on soil movement, examples of precipitation amounts required to induce overland flow in the region were sought as thresholds for comparison to Cascabel. In a study conducted on a pinyon-juniper woodland site in north-central New Mexico, Wilcox et al. (2003) found that a minimum of 0.59 inches (1.50 cm) of precipitation was generally needed to produce overland flow. On the Lucky Hills Watershed near Tombstone, Arizona, Osborn and Lane (1969) reported that storm events that averaged 0.32 inches (0.81 cm) produced overland flow, with events as small as 0.15 inches (0.38 cm) the minimum for overland flow to occur. Given the shallow soils at the Cascabel study site, daily precipitation event totals of 0.35 inches (0.89 cm) or more were assumed to be a "conservative" estimate for overland flow to occur.

There were 72 days in which a minimum of 0.35 inches (0.89 cm) of precipitation fell on the watersheds. The greatest number of 0.35 inch (0.89 cm) or greater events for a measurement period (18) occurred in the cool season leading up to measurements in the spring of 2005; this was the period with the highest soil erosion rate and third highest amount of deposition. Comparison of the number of 0.35 inch (0.89 cm) precipitation

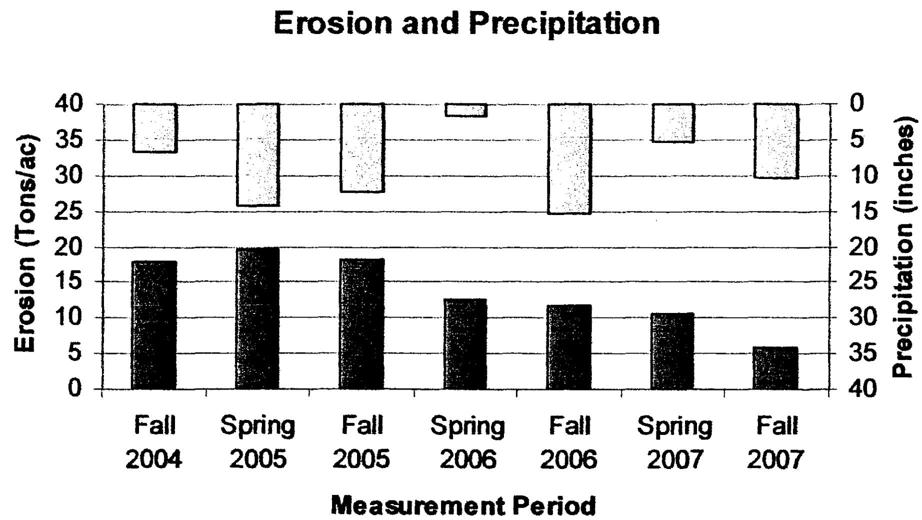

Figure 3. Accumulated precipitation (top) and corresponding soil erosion (bottom) by measurement period for the Cascabel Watersheds. Note: Conversion of erosion rates from Tons/ac to a metric equivalent (Mg/ha) can be achieved by multiplying erosion values by 2.24. Conversion of precipitation amounts from inches to a metric equivalent (mm) can be achieved by multiplying precipitation values by 25.4.

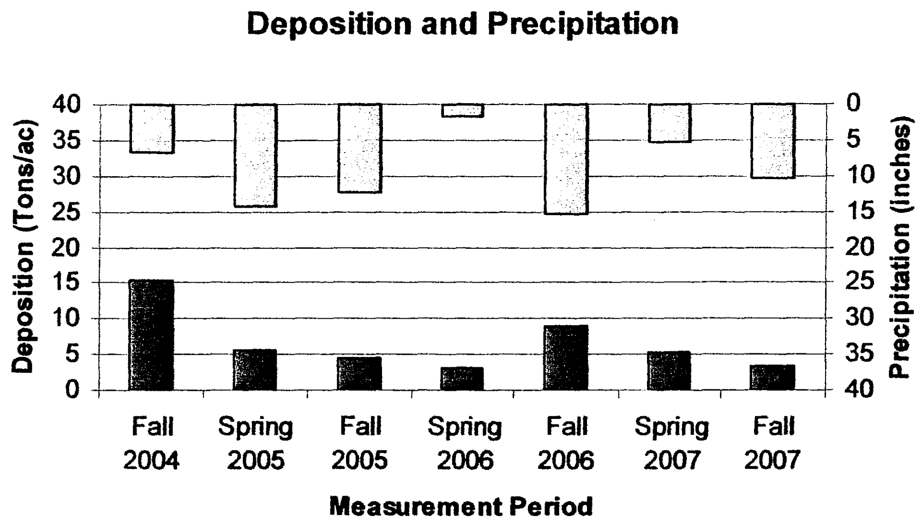

Figure 4. Accumulated precipitation (top) and corresponding soil deposition (bottom) by measurement period for the Cascabel Watersheds. Conversion of deposition rates from Tons/ac to a metric equivalent (Mg/ha) can be achieved by multiplying deposition values by 2.24. Conversion of precipitation amounts from inches to a metric equivalent (mm) can be achieved by multiplying precipitation values by 25.4.

events for a measurement period with the corresponding average erosion and deposition measurements for the period using simple linear regression did not result in significant relationships, however. Additional sampling periods and evaluations of overland flow producing events specific to the Cascabel Watersheds might be helpful in testing this relationship further.

In addition to having the most number of days with 0.35 inch (0.89 cm) or greater events, the spring of 2005 also had the highest number of recurring storms. Higher soil moisture due to prior storms can lead to the infiltration capacity of soil being exceeded more rapidly with overland flow resulting. Syed et al. (2003) indicated that moisture can be lost in the upper few inches of the soil surface within five days of a precipitation event in southeastern Arizona. A more "conservative" estimate of storms that recurred within three days of an initial storm—both meeting the threshold of 0.35 inches (0.89 cm)—was used as a basis for antecedent moisture and a potential catalyst for more rapid overland flow to occur for this study. Recurring storms meeting this threshold occurred once in the fall of 2004, six times in the spring of 2005, three times in the fall of 2005, five times in the fall of 2006, and four times in the fall of 2007. The springs of 2006 and 2007 had no storms meeting this qualification. While the highest number of recurring storms occurred during the period with the highest erosion rates, simple linear regressions comparing storm recurrence events to average erosion and deposition for each period did not result in significant relationships. Comparison on an annual basis showed the nine total recurring events for the year of 2005 might explain the higher overall erosion rate for that year compared to erosion rates in 2006 and 2007 which had only five and four recurring events respectively. It is possible that successive storm events of a threshold specific to those that generated overland flow at the Cascabel study area, might better explain soil movement than the 0.35 inch (0.89 cm) value selected in this study.

Precipitation intensity can also result in soil particle detachment and could have resulted in soil movement at the study site. The rate of soil particle detachment by raindrops cannot be a proxy of erosion rate alone, however, without consideration of overland flow distribution and ground surface characteristics (Parsons et al. 1994). Therefore, determining precipitation intensities capable of detaching soil through rain splash and resulting in overland flow to transport the loosened soil was necessary. Syed et al. (2003) reviewed several studies before settling on 0.25 in/hr (0.64 cm/hr) as a threshold for runoff producing intensities in semi-arid southwestern watersheds.

There were 51 occurrences when rainfall intensities averaged 0.25 in/hr (0.64 cm/hr) for one hour at the study area. The majority of these events (88 percent) were during the summer monsoon measurement periods. There were no winter rains that met the 0.25 in/hr (0.64 cm/hr) threshold leading up to the spring of 2006 measurements and only one prior to the spring of 2007. Maximum rainfall intensities were also much greater during the monsoon seasons. The highest winter-period intensity of 0.39 in/hr (0.99 cm/hr) was exceeded on 20 occasions by storms in the monsoon periods. The intensity threshold chosen might have led to soil detachment—particularly during the monsoon seasons—but probably does not account for why the rates measured in the spring of 2005 accounted for the highest erosion rates measured over the three and half years of pre-treatment study.

The durations of storms and number of days with recorded precipitation were additional factors evaluated to test differences in soil movement rates by measurement periods.

Storm events in the periods leading up to spring erosion measurements (for example, winter precipitation) averaged nearly five hours in duration (4.98 ± 0.64 hrs) while the monsoonal events were less (3.21 ± 0.30 hrs). Storm durations are seen in Table 5. The mean duration of storms in the spring of 2005 specifically were not significantly different than other spring periods, but they did last significantly longer than average storm durations for each of the fall measurement periods. These storms of longer duration might have allowed for extended periods of overland flow capable of moving soil particles loosened, but not otherwise removed, from previously higher intensity events such as those described above. For example, in January of 2005 nearly three inches of rain was recorded at the study area leading to peak flows greater than 2 ft^3/sec on watershed A and 7 ft^3/sec on watershed I over the course of four days (Gottfried et al. 2006). The spring of 2005 also had the greatest number of days with recorded precipitation. Simple linear regression tests comparing storm durations to average erosion and deposition for each measurement period, as well as the number of days with recorded precipitation by average soil erosion and deposition for each measurement period did not result in any significant relationships.

Physiography

Of the 146 plots where measurements were taken, 49 were classified as upper, 65 as middle, and 32 as lower hillslope positions. Soil erosion rates were significantly different at these positions for measurements pooled across all periods. Specifically, soil

Table 5. Number of precipitation events and average storm durations with 90 percent confidence intervals for each measurement period.

Season	Days with a precipitation event	Mean storm length (hrs)
Fall 2004	43	2.65 ± 0.84
Spring 2005	65	5.60 ± 0.69
Fall 2005	48	3.21 ± 0.80
Spring 2006	14	4.07 ± 1.48
Fall 2006	64	3.27 ± 0.70
Spring 2007	44	4.36 ± 0.83
Fall 2007	39	3.74 ± 0.88

erosion rates of 9.77 tons/ac (21.89 Mg/ha) on upper hillslope positions were less than the soil lost on the middle hillslope (16.07 tons/ac or 36.00 Mg/ha) and lower hillslope (17.08 tons/ac or 38.26 Mg/ha) positions (Table 6). Greater soil erosion on middle hillslopes compared to upper hillslope positions coincides with the thinner soil profiles described by Jenny (1941) and Ruhe and Walker (1968) due to greater surface runoff at these middle hillslope locations. The absence of a statistical difference in erosion rates at lower and middle hillslope positions could be a result of hillslope position designations in this study being "less reflective" of slope shape or gradient than the categories defined by Ruhe and Walker (1968) in which hillslope profiles were assigned five possible designations (summit, shoulder, backslope, footslope, and toeslope). Some of the plots on lower hillslope positions near channels were more incised than concave in shape which would have meant that gradients were steeper. Rather than concave depositional areas, the average slope steepness at lower hillslope positions (23.0 percent) was statistically similar to middle hillslope positions (21.7 percent). Slope gradients at the upper hillslope positions (13.4 percent) were significantly less, which might account for why these sites experienced the lowest average erosion rates measured.

Despite the similar rates of erosion on lower and middle hillslope positions, increased deposition at lower hillslope positions, as also described by Ruhe and Walker (1968) was corroborated in the Cascabel study. As seen in Table 7, lower hillslope positions averaged 8.46 tons/ac (18.95 Mg/ha) which was significantly greater than the 5.44 tons/ac (12.19 Mg/ha) found on both middle and upper hillslope positions.

Table 6. Average soil erosion (tons/ac and Mg/ha) for a measurement period at the three hillslope positions.

Hillslope Position	Tons/ac	Mg/ha
Lower	17.08	38.26
Middle	16.07	36.00
Upper	9.77	21.89

Table 7. Average soil deposition (tons/ac and Mg/ha) for a measurement period at the three hillslope positions.

Hillslope Position	Tons/ac	Mg/ha
Lower	8.46	18.95
Middle	5.44	12.19
Upper	5.44	12.19

To further evaluate the effect of gradient on soil movement rates, slope percentages were compared to soil erosion and deposition at plots. Slope steepness encountered at the study area ranged from zero to 45 percent. The majority of these gradients (55 percent) were between 10 and 20 percent. Erosion on 40 percent slopes was significantly greater than on 10 and 15 percent slopes. Slopes of 35 percent also had statistically greater erosion than 10 percent slopes. Deposition rates were not found to significantly differ at any slope steepness. Erosion and deposition rates for each slope percentage are presented in Tables 8 and 9. It is not clear why changes in slope did not result in more statistical differences in erosion or deposition. It is possible that low sample sizes for deposition at 0, 40, and 45 percent slopes ($n = 2$, 6, and 2 respectively) and for erosion at 45 percent slopes ($n = 4$) might have limited statistical differences in soil movement at these locations. A second explanation could be a result of increased armoring of the soil surface by greater amounts of rock fragments at steeper gradients. Nearing et al. (2005) hypothesized that greater rock fragments left at steeper slopes—due to preferential stripping of fine soil material in the past—might lead to overland flow velocities becoming independent of slope gradients. The authors speculate that a "slope-velocity equilibrium" is established in which soil movement rates might become more uniform across hillslope gradients. In the case of the Cascabel study area, rock cover as a percentage of ground cover estimates generally increased with slope as seen in Table 10.

In addition to hillslope position and slope percentage, differences in soil movement were compared at different aspects. Hillslopes that receive greater amounts of solar radiation (south-facing slopes) are generally warmer with reduced soil moisture than slopes that receive less solar radiation (Brady and Weil 2000). Differences in aspect

Table 8. Average erosion (tons/ac and Mg/ha) at each slope percentage for a measurement period with sample sizes.

Slope	n	Tons/ac	Mg/ha
0	14	8.21	18.39
5	56	12.95	29.01
10	82	10.53	23.59
15	93	12.14	27.19
20	109	13.1	29.34
25	63	13.7	30.69
30	49	21.71	48.63
35	57	18.79	42.09
40	18	22.42	50.22
45	4	14.71	32.95

Table 9. Average deposition (tons/ac and Mg/ha) at each slope percentage for a measurement period with sample sizes.

Slope	n	Tons/ac	Mg/ha
0	2	6.7	15.01
5	23	6.35	14.22
10	31	4.18	9.36
15	41	7.36	16.49
20	44	6.15	13.78
25	21	8.61	19.29
30	18	4.74	10.62
35	15	5.84	13.08
40	6	4.63	10.37
45	2	16.78	37.59

Table 10. Average rock percentage (as a proportion of ground cover) by slope gradient. Note that small sample sizes could be impacting the lower amounts of rock cover at 45 percent slopes and higher amounts at zero percent slopes.

Slope	n	Mean rock percentage on soil surface
0	3	40.89
5	15	23.44
10	22	26.53
15	27	34.32
20	31	32.29
25	16	37.13
30	14	43.33
35	13	48.65
40	4	52.08
45	1	33.33

might influence vegetation or freeze-thaw processes which in turn might influence soil movement. Forty-seven percent of the aspects at the study site were either east- or west-facing. The high proportion of these two aspects was not surprising considering that the main channels for each watershed generally flow north to Walnut Creek or south to Whitmire Creek. Erosion was greater at north facing aspects, where soil loss averaged 20.81 tons/ac (46.61 Mg/ha), than at south facing aspects where soil loss in each measurement period averaged 11.08 tons/ac (24.82 Mg/ha). Some pins at north-facing aspects, based on anecdotal observation, appeared to be elevated above loosened or heaved soil rather than soil that had been stripped or eroded from overland flow processes. It is possible that pins could have been heaved upward as well, however, without additional information or monitoring it is difficult to determine whether freeze-thaw processes might have been responsible for differences in erosion rates at north- and south-facing aspects. Comparison of deposition at different aspects did not reveal any significant differences. Soil erosion and deposition for each aspect can be seen in Tables 11 and 12 respectively.

Slope-Aspect

Moir et al. (2000) reported greater erosion rates on steep south-facing slopes of the Peloncillo Mountains. Slope and aspect combinations were evaluated to determine whether a physiographic interaction between the two factors affected soil movement rates. Langley measurements (unit equal to 1 gram calorie/cm^2 of irradiated surface) for slopes and aspects at 32° N latitude presented by Frank and Lee (1966) were used as an

Table 11. Average erosion (tons/ac and Mg/ha) at each aspect for a measurement period.

Aspect	tons/ac	Mg/ha
E	14.01	31.38
N	20.81	46.61
Level	8.21	18.39
NE	10.03	22.47
NW	10.53	23.59
S	11.08	24.82
SE	14.56	32.61
SW	11.89	26.63
W	16.32	36.56

Table 12. Average deposition (tons/ac and Mg/ha) at each aspect for a measurement period.

Aspect	Tons/ac	Mg/ha
E	6.70	15.01
N	5.39	12.07
Level	6.70	15.01
NE	6.25	14.00
NW	6.70	15.01
S	6.85	15.34
SE	6.20	13.89
SW	5.04	11.29
W	6.30	14.11

index for relating these physiographic factors to soil movement rates. Spring and fall erosion measurements were significantly related to index values for February 20 and July 27 (midpoint measurement period dates), however, statistical inferences were not warranted due to exceedingly small r^2 values ($r^2 = 0.07$; $r^2 = 0.02$ respectively). Simple linear regression tests did not reveal significant relationships between deposition measurements and the Langley measurement index for the respective midpoint dates.

Vegetation

Examination of the crown closure of tree overstory revealed that almost 70 percent of the erosion plots measured had no measured crown closure. This value reflects the open nature of an oak savanna. Nevertheless, the distribution of crown closure at a plot ranged up to 100 percent. Simple linear regressions showed that erosion was negatively related to crown closure while deposition was positively related to crown closure. It is possible that the added protection from raindrop impact provided by thicker or larger crown closure allowed for greater deposition with the opposite being the case on more exposed plots. The predictive power of both relationships was low however (erosion $r^2 = 0.01$; deposition $r^2 = 0.02$), and would not assist in explaining the variability in soil deposition and erosion measurements.

While increased crown closure can lessen raindrop impact, a greater number of trees/ac could conceivably provide more obstructions needed to reduce runoff and erosion as described by Tongway and Ludwig (1997) and Davenport et al. (1998) for semi-arid ecosystems. The number of trees/ac measured at the Cascabel study site ranged from 0 to 328 (0 to 810 trees/ha). Analysis of soil movement showed that erosion and deposition were both positively related to tree density, but similarly to crown closure, the predictive power was low in both instances (erosion $r^2 = 0.01$; deposition $r^2 = 0.08$).

While tree density did not help to explain the variability in soil movement at Cascabel, other studies have shown that herbaceous understory can lessen soil loss (Paige et al. 2003; Nearing et al. 2005). Nearing et al. (2005) reported that on sites in southeastern Arizona with greater grass cover, overland flow was obstructed by vegetation and erosion rates reduced. The mean herbage production by season on the Cascabel Watersheds ranged from 67.6 lbs/ac (75.6 kg/ha) in the spring of 2006 to 458.7 lbs/ac (512.8 kg/ha) in the fall of 2007. Individual plot estimations ranged from 0 to 1,530.0 lbs/ac (0 to 1,710.5 kg/ha) with a mean of 231.4 lbs/ac (258.7 kg/ha). While a significant negative relationship between erosion and herbage production at Cascabel is similar to the findings of Nearing et al. (2005), little of the variation in erosion measurements could be explained by herbage estimates ($r^2 = 0.03$). It is possible that more intensive herbage measurements around soil movement pins might have assisted in eliminating more of the variability in the relationship between erosion and herbage cover. Deposition was not found to significantly relate to herbage production at the study area.

POST-FIRE MEASUREMENTS

Comparison of Treatments

The second objective of this study was to evaluate whether erosion and deposition differed depending on fire treatments. Comparisons of the initial post-fire mean erosion and deposition rates for the warm season and wildfire watersheds and the second measurements from the cool season watersheds were made using Friedman's analysis of variance by ranks test with a random block design (Zar 1999). The test resulted in no statistical difference between the fire treatment effects on erosion or deposition and, therefore, measurements from the fall 2008 period were pooled. Soil erosion rates amounted to 11.54 tons/ac (25.85 Mg/ha) across plots for the measurement period, while deposition rates for the period averaged 7.10 tons/ac (15.90 Mg/ha) for the same period. The absence of statistical differences in erosion and deposition depending on fire treatment could be a result of the generally low severity of fire effects on soil indicated by Stropki et al. (2009). Approximately 90 percent of plots on watersheds burned by each fire treatment showed no water repellency leading the authors to hypothesize that that changes to overland flow would have been "relatively minor." This could have resulted in erosion and deposition—as a response to overland flow—being limited as well. Monitoring should continue to determine if differences in burn seasons or burn severities lead to differences in soil movement rates over time. Comparisons of post-fire soil movement for various plot characteristics such as physiographic differences and vegetative cover should also be evaluated for future managerial decisions.

Cool Season Burns

Measurements of soil movement for the spring of 2008 period were obtained nine weeks after the cool season burns. Mann-Whitney tests used to compare erosion and deposition on four cool season burned watersheds to erosion and deposition on eight unburned watersheds for this period revealed no significant difference. Therefore, the measurements from the burned and unburned watersheds were pooled to determine the mean soil erosion and deposition for the period. An average of 16.88 tons/ac (37.80 Mg/ha) of soil was eroded across plots in the spring of 2008 which was significantly greater than the previous fall's soil loss of 5.84 tons/ac (13.09 Mg/ha). Average deposition for the spring of 2008 amounted to 3.73 tons/ac (8.35 Mg/ha) and was less than the falls of 2004 and 2006 which averaged 15.26 tons/ac (34.19 Mg/ha) and 9.02 tons/ac (20.20 Mg/ha) respectively.

Mann-Whitney tests were also used to compare pre- and post-fire mean erosion and deposition rates for the four watersheds that experienced the cool season burn (that is, C, H, K, and N). Post-fire deposition in the spring of 2008 did not significantly differ from pre-fire estimates, however post-fire erosion estimates during the spring of 2008 were significantly higher than pre-fire erosion rates. Erosion averaged 13.45 tons/ac (30.13 Mg/ha) prior to the cool season burns and 21.81 tons/ac (48.86 Mg/ha) in the first measurement period after the fires. To determine if the higher post-fire erosion rates persisted, the spring of 2008 post-fire measurements from the cool season burned watersheds were pooled with the following season's measurements and compared to pre-fire estimates. Comparisons showed that pre-fire rates of 13.45 tons/ac (30.13 Mg/ha) were statistically similar to the combined spring and fall 2008 post-fire erosion rates of

13.90 tons/ac (31.15 Mg/ha). While these rates might suggest that erosion rates returned to pre-fire conditions, it is premature to define any trends after only two seasons of post-fire measurement.

Warm Season Burns

Mann-Whitney tests showed that post-fire erosion and deposition rates on the three watersheds (that is, A, Eb, and F) that experienced a warm season burn were statistically similar to the pre-fire soil erosion and deposition rates measured before the fall of 2008. The absence of water repellency for approximately 90 percent of the plots and low severity impacts on soil reported by Stropki et al. (2009) might explain the lack of statistical differences in erosion and deposition before and after the warm season fires.

Wildfire Burns

Pre- and post-fire mean erosion rates on the watersheds burned by the wildfire (that is, B, G, I, J2, and M) did not significantly differ. Pre- and post-fire deposition on these same watersheds did statistically differ however. Prior to the wildfire deposition averaged 5.79 tons/ac (12.98 Mg/ha) which was less than the 7.61 tons/ac (17.04 Mg/ha) after the fire. This outcome was surprising considering that the warm season burns conducted one day prior to the wildfire did not result in any differences in pre- and post-fire deposition rates. Major differences were not found between the occurrence of water repellent soils for both burn types (Stropki et al. 2009), although the effects of the fire treatments on tree overstory has yet to been analyzed. In the event that the wildfire had a greater impact on tree overstory than the warm-season fire, raindrop interception and subsequent soil displacement might have been affected differently as well. As Paige et al. (2003) noted after the Ryan Wildfire, despite a reduction in sediment yield one year after the fire, runoff increased indicating that productivity of herbaceous plant cover might have decreased and recovery would take longer than anticipated. Additional monitoring at the Cascabel study area is warranted to determine if differences in deposition after the wildfire persist and whether differences are related to the recoverability of the site. It would also be worth examining whether deposition continued to be greater at lower hillslope positions as it had been prior to burning.

CONCLUSIONS

Results from this study provide estimates of soil movement rates on oak savannas of the Southwestern Borderlands Region and factors that might influence changes in those rates. The analysis also summarizes the initial results of soil movement after three different fire treatments. Statistically significant differences in erosion and deposition as influenced by different factors can be seen in Table 13. Soil loss in 2005, which amounted to 27.56 tons/ac (61.73 Mg/ha), exceeded erosion in 2006 and 2007 which was estimated at 12.54 tons/ac (28.09 Mg/ha) and 12.65 tons/ac (28.34 Mg/ha) respectively. Deposition did not vary by year, but was statistically different between fall and spring measurement periods. Seasonal differences in deposition were specifically different between the spring and fall of 2006 with estimates amounting to 2.97 tons/ac (6.65

Table 13. Temporal and plot variables that significantly influenced erosion and deposition rates at the Cascabel study site.

EROSION

Explanatory Variable	Result	Test Used
Years	2005 > 2006 & 2007	Nemenyi
Hillslope Position	Upper < Middle & Lower	Nemenyi
Slope	40% > 10% & 15%	Nemenyi
	35% > 10%	
Aspect	North-facing > South-facing	Nemenyi
Cool Season Fire	Post-fire > Prefire	Mann-Whitney

DEPOSITION

Explanatory Variable	Result	Test Used
Season	Spring < Fall	Mann-Whitney
Hillslope Position	Lower > Middle & Upper	Nemenyi
Wildfire	Post-fire > Prefire	Mann-Whitney

Mg/ha) and 9.02 tons/ac (20.21 Mg/ha) respectively. While threshold precipitation events and intensities, recurring storms, and additional storm factors examined did not directly relate to rates of soil movement, it is worth noting that the higher erosion rates of 2005 occurred during the period with the greatest annual precipitation and included several large storm events which are outlined in Gottfried et al. (2006). Also, the disparate deposition rates in the spring and fall of 2006 occurred during the measurement periods with the least and most precipitation respectively (see Figure 4).

Physiographic influences on erosion and deposition were also apparent at the study site. Analysis showed that upper hillslope positions, which averaged 9.77 tons/ac (21.89 Mg/ha) soil erosion, lost less soil than middle and lower hillslope positions which averaged 16.07 tons/ac (36.00 Mg/ha) and 17.08 tons/ac (38.26 Mg/ha) erosion respectively. Deposition on the other hand, was statistically greater on lower hillslope positions than on middle or upper hillslopes. Deposition on lower hillslopes averaged 8.46 tons/ac (18.95 Mg/ha) and 5.44 tons/ac (12.19 Mg/ha) on both of the other positions. These results are similar to soil movement processes described by Ruhe and Walker (1968) in which erosion was greater at middle hillslope positions and deposition higher at lower hillslope positions.

Analysis of physiographic changes also showed erosion to differ at certain slope percentages and aspects. Specifically, erosion was greater on 40 percent slopes than on 10 or 15 percent slopes and it was greater on 35 percent slopes than on 10 percent slopes. The absence of more erosional and depositional differences at varying slopes could be a result of soil surface armoring by higher amounts of rock fragments at steeper gradients, although it is unclear why the 20.81 tons/ac (46.61 Mg/ha) of erosion at north-facing aspects exceeded soil loss at south-facing aspects which averaged 11.08 tons/ac (24.82 Mg/ha).

Additional analysis comparing erosion and deposition to slope-aspect interactions, as well as tree overstory and herbaceous understory characteristics, either did not result in significant relationships or the predictive power of the relationships was too low to be of assistance in explaining variability in soil movement measurements.

It is too early to define any trends in post-fire soil movement rates, but initial comparisons between all three burns did not reveal any statistical differences. Pre- and post- cool season fire measurements showed accelerated erosion one season after the cool season burn, but no significant difference two seasons after the fire. Deposition increased after the wildfire, but no significant differences in erosion or deposition were detected after the warm season burn. Further analysis as to whether fire treatments affected tree overstory differently—and in turn interception of raindrop impact—might assist in explaining why differences existed between pre- and post-fire deposition rates on the watersheds treated by the wildfire but not on the watersheds treated by the warm season burn. Since disturbances to semi-arid sites have been shown to exacerbate soil movement rates, monitoring of these sites should continue to determine whether the increased deposition after the wildfire persists and where it might be most accelerated depending on plot characteristics.

MANAGEMENT IMPLICATIONS

The use of prescribed fire has been proposed as a management tool to control woody plant encroachment and create a mosaic of vegetation in southwestern oak savannas. A mosaic of vegetation would include a combination of open grassland with patches of tree and shrub overstory. The vegetative benefits gained through the application of prescribed fire however, might be compromised on some areas if erosion rates increase as a consequence of those fires. Results from this study indicate that before fire treatments were initiated, hillslope erosion rates on southwestern oak savannas were higher at some steeper gradients compared to lesser slopes and on middle hillslope positions compared to upper hillslope positions. While it is not evident where all of this soil loss is redeposited, there were higher rates of deposition on lower hillslope positions which are generally closer to channels. Managers of these ecosystems should consider the potential risks to upland soils and downstream channels while implementing plans that might further exacerbate soil movement rates such as through the construction of new roads, establishment of grazing allotments, or by initiating fires. Failure to take necessary precautions at sites more vulnerable to soil movement could lead to greater mitigation costs and potentially a critical loss of soil due to the generally shallow composition of soils in oak savannas.

Where relationships between soil movement rates and plot characteristics were not significant, managers should still exert caution while implementing plans that have been shown to alter rates of soil loss in other studies. For example, while the varying presence of an herbaceous cover and tree overstories were not found to influence soil movement on the Cascabel Watersheds in a predictable way, alterations to these variables might still have consequences on erosion rates. Further examination of vegetation type or organic matter as a groundcover variable could help to better define whether a relationship between soil movement and vegetation exists.

Results presented in this study also indicated that the first season of warm season and wildfire erosion and deposition rates, and the second season of cool season erosion and deposition measurements, did not significantly differ by burn treatments. The initial absence in differences could be a result of the low severity effects on soils generally found across fire treatments (Stropki et al. 2009). With approximately 90 percent of plots across all fire treatments not showing any water repellency, potential increases in overland flow and erosion after disturbance by fire might have been negated.

Despite the absence of treatment differences, it is premature to declare that fire will not affect soil movement rates in oak savanna ecosystems. Initial measurements of post-fire erosion rates after cool season burns were higher than pre-fire rates and post-fire deposition after the wildfire was higher than pre-fire rates. The absence of any differences in deposition after the warm season burns, despite occurring only one day prior to the wildfire, raises questions about whether additional factors might have impacted post-fire soil movement rates. Examination of the impacts of these fires on tree overstory is ongoing, but might provide indications as to whether the fire treatments affected the canopy differently and if that might have subsequently influenced raindrop interception and soil movement. Comparison of soil movement rates at different physiographic positions also has not been evaluated. Given that recovery of sites to pre-fire levels of soil erosion might be less likely on steeper slopes after a disturbance

(Wilcox et al. 2003), caution should be exerted not to over-extrapolate post-fire results without continued monitoring and evaluation.

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