

The Effects of Fire on Soil Hydrologic Properties and Sediment Fluxes in Chaparral Steeplands, Southern California¹

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Abstract

Fire is a major disturbance event in southwestern ecosystems. A prescribed burn in the San Dimas Experimental Forest provided an opportunity to quantify the effects of fire on soil hydrologic properties and sediment fluxes in chaparral-covered steplands. Located in the San Gabriel Mountains about 50 km northeast of Los Angeles, a 1.28 ha watershed was instrumented with hillslope sediment collectors and a debris basin. Sediment fluxes were measured for seven years prior to the fire and through the first post-fire winter. Soil samples taken just before and after the fire were analyzed for bulk density, texture, and moisture content. Soil non-wettability was determined pre- and post-fire at the same 105 locations using the water drop penetration test. Post-fire soils were denser, coarser, and much drier than prior to the burn. Although extremely variable, non-wettability generally increased after the fire. Post-fire hillslope erosion was twice as great as pre-burn levels during the dry season and increased by 10-fold in the wet season, despite a record drought year. Post-fire sediment yield was 20 times greater than the unburned annual average. We believe the fire-induced changes in soil properties coupled with reduced ground cover caused an increase in surface runoff that accounts for the large increases in post-fire sediment fluxes.

Introduction

Fire is a major disturbance event in semiarid southwestern ecosystems. Fire incinerates vegetation, alters soil properties, and renders the landscape susceptible to the forces of gravity, running water, and wind. Under these conditions, accelerated post-fire erosion is inevitable. This accelerated post-fire erosion is accentuated in the southern California mountains because of steep topography, non-cohesive soils, and intense rainfall events (Rice 1974). Often these factors combine to produce debris flows with great destructive power (Wells 1987).

At the wildland/urban interface (WUI) in southern California, where the fringes of urban development impinge on adjacent steep mountain fronts, accelerated post-fire erosion can seriously harm human communities. Lives are threatened, property is jeopardized, and infrastructure (roads, bridges, pipelines, utility lines) is placed at risk. Uncertainty about the magnitude of destruction associated with accelerated post-fire erosion stems from our limited ability to predict specific post-fire watershed responses. Unfortunately, prediction, usually in the form of risk assessment and planning that involves numerical modeling, can only derive from a sufficient understanding of the erosion problem and the quantification of fire effects and erosion processes.

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A prescribed burn in the San Dimas Experimental Forest provided an opportunity to document and quantify the effects of fire on soil hydrologic properties and sediment fluxes within a small watershed unit in a semiarid, chaparral-covered, steep-land ecosystem. Results of this research could serve as a benchmark against which to test existing predictive models of post-fire erosion for the southern California area.

Study Site

Located in the San Gabriel Mountains about 50 km northeast of Los Angeles, the San Dimas Experimental Forest has been a wildland research site for hydrology and ecology for nearly seventy years (*fig. 1*). In conjunction with an ongoing fuel reduction operation, we selected a 1.28 ha chaparral-covered study watershed that was part of a 4 km² prescribed burn project. Situated at an elevation of about 1,000 m on a southerly aspect, hillslope angles in the study watershed average 31° (60 percent) and stream channel gradients average 21° (35 percent). The region experiences a Mediterranean climate regime, with cool, wet winters and hot, dry summers. Precipitation, falling almost exclusively as rain between the months of November and March, averages about 700 mm annually (Dunn and others 1988). Crystalline metamorphic and intrusive igneous bedrock produces non-cohesive sandy loam soils (coarse-loamy, mixed, thermic Typic Xerorthents) that support a mixed chaparral vegetation assemblage dominated by ceanothus (*Ceanothus crassifolius*), chamise (*Adenostoma fasciculatum*), and scrub oak (*Quercus berberidifolia*) (Dunn and others 1988).

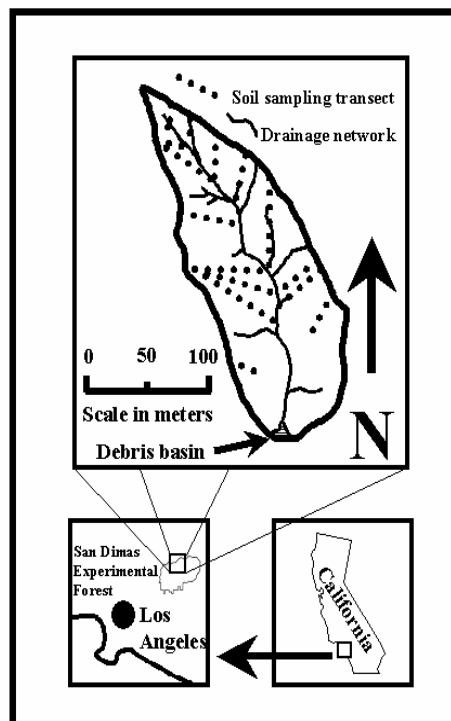


Figure 1—Location map of the study watershed showing the soil sampling transects.

Methods

To determine soil properties, we chose eight transects that crossed the watershed in a chevron pattern (*fig. 1*). Six to eight sample locations were randomly chosen along each transect, resulting in a total of 54 sampling sites. The soil characteristics were measured at the same locations at a depth of 0 to 5 cm both before and after the fire. Particle size distribution was determined for the mineral soil by the pipette method using samples that were sieved to remove coarse fragments greater than 2 mm in diameter (Gee and Bauder 1986). Percent gravel was determined by weighing the portion remaining in a 2 mm sieve. Soil bulk density was determined by the core method (Blake and Hartge 1986). Subsequent determinations of the volume and mass of rock fragments greater than 2 mm were subtracted from the aggregate samples to yield a corrected bulk density (Vincent and Chadwick 1994). Porosity was calculated from bulk density assuming a particle density of 2.65 g cm⁻³ (Danielson and Sutherland 1986). Water content measurements were made gravimetrically on soil samples taken at 0 to 3 cm depth (Gardner 1986).

An average duff and litter depth was determined using the 4-corners and 1 mid-point of a 50 cm x 50 cm square at the 54 locations throughout the watershed. Litter and duff reduction was determined using steel pins (20 cm in length) that were installed flush with the duff surface at 105 sampling points. The distance of the head of the pin protruding above the mineral soil after fire was measured to determine duff and litter consumption. Soil non-wettability was determined by the water drop penetration test (DeBano 1981) at the same 105 sampling points.

We measured hillslope sediment fluxes in 30 cm aperture collector traps on unbounded plots (Wells and Wohlgemuth 1982). Seventy-five traps scattered throughout the watershed quantified both hillslope erosion and sediment delivery to the stream channels. Hillslope sediment fluxes are measured as the air-dried mass of collected debris per unit width of slope contour (kg m⁻¹). We measured watershed sediment yield in a debris basin behind an earthen dam. Repeated sag tape surveys at monumented cross sections recorded the deposition of sediment flushed out of the small watershed (Ray and Megahan 1978). Sediment fluxes were measured for seven years prior to the fire and through the first post-fire winter.

Results and Discussion

Prescribed Burning

The prescribed burning occurred on May 15, 2001, and the fire burned for 1 to 3 hours in the target watershed. Burn severity was estimated qualitatively from post-fire fuel size diameter, color of ash, and degree of litter and duff consumption (Wells and others 1979). The fire consumed the chaparral vegetation in a period of less than 30 minutes, leaving only charred skeletal remains. Residual chamise fuel tip diameters were less than 6 mm on the site, indicating a uniform burn with light severity in the aboveground foliage (Wells and others 1979). However, ground fuels continued smoldering for several hours, consuming considerable amounts of litter and duff, indicative of a fire of moderate to high severity. Thus, a burn that appears to be of light severity in the vegetative canopy may result in a burn of greater severity at the soil surface.

Soil Properties

Soil properties from before and after the fire are shown in *figure 2*. Results of particle size analyses indicate an increase in the silt fraction at the expense of both sand and clay. This suggests that sand-sized aggregates are breaking down, perhaps as organic material is incinerated. Heating to 250° C can decrease soil organic matter content by 30 percent (Giovannini and others 2001). The 39 percent reduction in the clay fraction coupled with the increase in silt indicates that there was some aggregation of fines into silt-sized particles (Ulery and Graham 1993). Soil heating to 250° C can be sufficient to aggregate clay particles to silt and sand sizes (Giovannini and others 2001). The increase in percent gravel may be related to the post-fire release of greater than 2 mm material from the litter and duff layers, which then becomes intermixed in the disturbed surface soil.

The fire reduced the median litter depth across the watershed from 22 cm to 3 cm. In many cases the litter and duff layers were totally consumed in the smoldering ground fire. Areas where litter remained after the fire consisted of an amalgamation of ash, char, and loose mineral soil. The patterns of duff consumption reflected the species composition of the pre-fire vegetation.

Bulk density increased by 27 percent after the fire, leading to a similar decrease in calculated porosity. This suggests that the combustion of low-density organic material was not confined to the litter and duff layer, but extended into the mineral soil as well. Not surprisingly, soil moisture was reduced by 69 percent after the burn, attesting to the heat and residence time of the ground fire. Soil non-wettability is described in detail in an accompanying paper (Hubbert and others, this volume).

Sediment Fluxes

Results from the hillslope collector traps are displayed as cumulative totals (*fig. 3*). The number, order, and magnitude of storm events that produced more than 5 cm of rain are shown on the same graph. Activity levels or erosion rates correspond to the slope of the line graph. Prior to the fire, sediment flux was fairly constant, with slightly greater wet season erosion than dry season erosion (*fig. 3*). However, post-fire hillslope erosion was twice as great as pre-burn levels during the dry season, roughly equivalent to the pre-fire wet season rate. Moreover, during the initial post-fire wet season, erosion increased by 10-fold compared to pre-fire wet season levels, despite a record drought year. These results agree with previous studies of post-fire hillslope erosion in southern California chaparral ecosystems (Wohlgemuth and others 1998). During and immediately after the fire, erosion increases on these steep hillsides as surface organic barriers within the litter and duff layers are consumed, liberating the sediment trapped behind them. Erosion rates remain elevated, as the burned landscape with altered soil properties is sensitive to even minor disturbances (animal traffic, micro-earthquakes, etc.). With the onset of winter rains, a second flush of post-fire erosion occurs. This wet season erosion is enhanced by the lack of protective vegetation and organic litter, and the presence of non-wettable soils that can produce extensive overland flow.

Results from the debris basin surveys, along with the rain events, are displayed in *figure 4*. Prior to the fire, sediment yield was variable and did not always correspond to storm rainfall (*fig. 4*). However, first-year post-fire sediment yield was 20 times greater than the unburned annual average and 200 times greater than the annual median, despite a record drought year. This is similar to results from larger watersheds from the same general area (Rowe and others 1954).

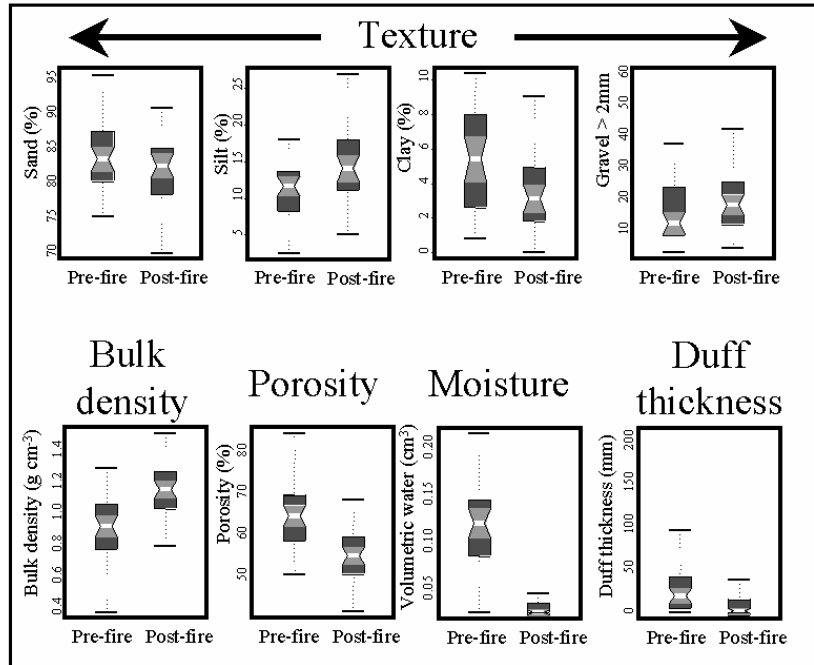


Figure 2—Selected soil properties from before and after the fire. White bar in middle of the box represents the median, with the notch representing the approximate 95 percent confidence band. Solid body of the box indicates the interquartile range. Lines outside the box show the range.

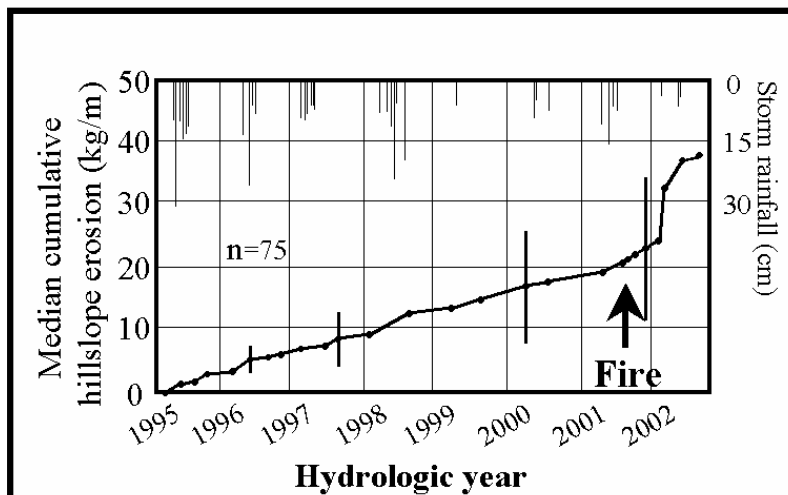


Figure 3—Cumulative median hillslope erosion and storm rainfall over time. The heavy vertical lines show the interquartile range of selected data points.

Sediment yield is a spatially integrated measure of erosion across a watershed unit. Although sediment yield is driven exclusively by surface runoff in the stream channels, it also reflects sediment delivery from the hillsides, the amount of sediment previously stored in the channels, and the time since the last channel-flushing event. The prescribed fire occurred in the midst of a four yr drought, culminating in the first post-fire winter as the driest season in 70 yr of record (Dunn and others 1988). Thus, while there was ample sediment stored in the stream channels that was subsequently mobilized by the initial post-fire storm events, the results were undoubtedly muted

compared to the response that would have been experienced with normal rainfall patterns.

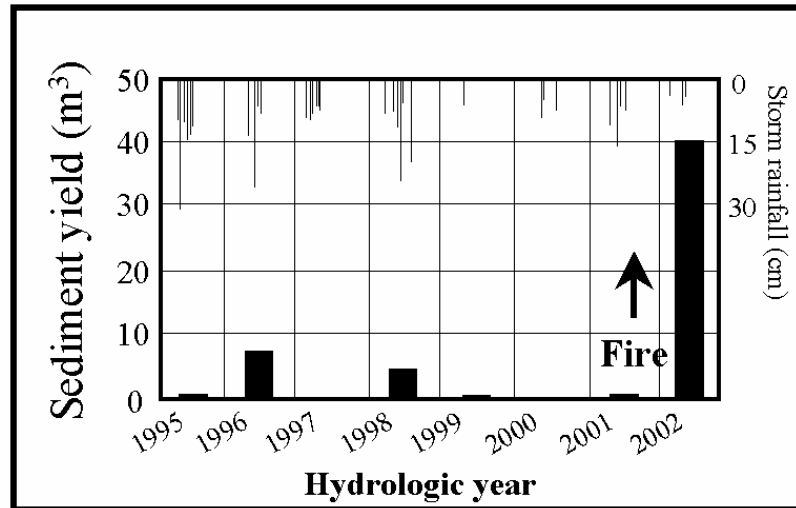


Figure 4—Sediment yield and storm rainfall over time for the 1.28 ha watershed.

Conclusions

Fire is a major disturbance event in chaparral ecosystems. Fire alters soil physical characteristics, rendering them denser, coarser, and much drier. The litter and duff layer is greatly reduced, and in many areas may be totally consumed. Although the sediment fluxes in the study watershed increased by an order of magnitude after the prescribed burn, the response was no doubt subdued compared to a wildfire followed by average rainfall. We believe the fire-induced changes in soil properties coupled with reduced ground cover caused an increase in surface runoff that accounts for the large increases in post-fire sediment fluxes.

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