# HILLSLOPE EROSION AND SMALL WATERSHED SEDIMENT YIELD FOLLOWING A WILDFIRE ON THE SAN DIMAS EXPERIMENTAL FOREST, SOUTHERN CALIFORNIA

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**Abstract**: In 2002, a wildfire burned over an ongoing sediment flux study in the steep San Gabriel Mountains of southern California. The study was conducted on the chaparral-covered San Dimas Experimental Forest, the site of previous vegetation type-conversions and prescribed burning. Hillslope erosion was measured with metal collector traps on unbounded plots in four catchments. Small watershed sediment yield was measured in debris basins in 17 catchments. Annual erosion did not correlate with maximum 15-minute rainfall intensities. Both hillslope erosion and sediment yield showed remarkable similarities in the post-burn environment. Erosion increased by one to two orders of magnitude in the first year after the fire compared to unburned levels, followed by a relatively rapid recovery to baseline values. Prescribed fire and wildfire produced similar post-fire erosion responses.

## INTRODUCTION

In southern California chaparral environments, the vegetation communities are adapted to prolonged summer drought. However, these adaptations, which include waxy or resinous leaves, produce fuels that are extremely flammable. In these fire-prone ecosystems, wildfire is a significant disturbance event that incinerates vegetation, alters soil properties, and renders the landscape susceptible to the agents of erosion. Under these conditions, increased sediment transport in upland watersheds is inevitable.

In the mountains of southern California, increased post-fire erosion is accentuated because of steep topography, non-cohesive soils, and intense rainfall events. This accelerated erosion can cause environmental site degradation, can extirpate refugia populations of endangered species, and can seriously harm downstream human communities at the wildland/urban interface. Lives are threatened, property is jeopardized, and corporate infrastructure (roads, bridges, pipelines, utility lines) is placed at risk.

Although the patterns of post-fire erosion on chaparral landscapes in southern California are generally understood, uncertainty about the magnitude of post-fire erosion events limits our ability to predict specific post-fire watershed responses. Unfortunately, prediction, usually in the form of risk assessment and planning that involves numerical modeling, is only possible with a sufficient understanding of the erosion problem along with the quantification of fire effects on erosion processes.

A wildfire on the San Dimas Experimental Forest that burned over an ongoing sediment flux study provided an opportunity to document and quantify the effects of fire on hillslope erosion and sediment yield in small watershed units in a semiarid, chaparral-covered, steepland environment. Results of this research could serve as a benchmark against which to test existing models of post-fire erosion for the southern California area.

**Background**: Semiarid geomorphic systems are characterized by high rates of sediment production (Langbein and Schumm, 1958), as the erosive rains attack significant areas of bare ground. In the steep mountains of southern California, weathered rock debris combines with organic litter to form thin, colluvial soils (DeBano, 1974). This sediment, stored on the hillslopes, is shed quasi-continuously by the gravitational process of dry ravel and the hydrologic processes of rainsplash and overland flow (Rice, 1974). Sediment accumulates in the ephemeral channels where it is periodically scoured by surface runoff and debris flows, generated by infrequent high magnitude storms, and routed primarily as bedload to the watershed outlet (Scott and Williams, 1978).

Fire magnifies the erosion hazard in mountainous southern California by reducing the resistances to the agents of erosion. The removal of the vegetation canopy and surface organic material decreases rainfall interception, and the denuded hillsides are subjected to unimpeded raindrop impacts (Rice, 1974). In addition, the combustion of soil organic matter can create a subsurface water-repellent layer that restricts infiltration and promotes overland flow (DeBano, 1981), enhancing surface runoff and concomitant sediment yield. In southern California, first-year post-fire sediment yield is 35 times greater on average than comparable unburned annual levels (Rowe et al., 1954).

**Study Area**: The San Dimas Experimental Forest (SDEF) is a nearly 7000 ha research preserve administered by the USDA Forest Service, Pacific Southwest Research Station (Figure 1). With its headquarters at Tanbark Flat (34° 12' N latitude, 117° 46' W longitude), the SDEF is located in a front range of the San Gabriel Mountains about 45 km northeast of Los Angeles, California. The SDEF was established in the early 1930s to document and quantify wildland hydrology in the semiarid chaparral-covered steeplands of southern California.

Topography in the SDEF consists of a highly dissected mountain block with narrow, steep-walled canyons (slope angles average 68 percent) and steep channel gradients (average of 15 percent). Elevations in the study area range from 750 m to 1050 m. Bedrock geology is dominated by tectonically uplifted Precambrian metamorphics and Mesozoic granitics that produce shallow, azonal, coarse-textured soils (Dunn et al., 1988).

The SDEF experiences a Mediterranean climate, characterized by cool, moist winters and hot, dry summers. Mean annual precipitation, falling almost exclusively as rain, is 714 mm (72-year record), but rain during individual years can range from 252 to 1848 mm. Over 90 percent of the average annual precipitation falls between the months of November and April, with 10 percent of the storms producing over 50 percent of the total rain (Wohlgemuth, 1996).

Native vegetation in the SDEF consists primarily of mixed chaparral. Plant cover on south-facing slopes ranges from dense stands of chamise (*Adenostoma fasciculatum*) and ceanothus (*Ceanothus* spp.) to more open stands of chamise and sage (*Salvia* spp.). North-facing hillsides are dominated by scrub oak (*Quercus berberidifolia*) and ceanothus, with occasional hardwood trees – live oak (*Quercus agrifolia*) and California laurel (*Umbellularia californica*) – occurring on moister shaded slopes and along the riparian corridors (Wohlgemuth, 1996).

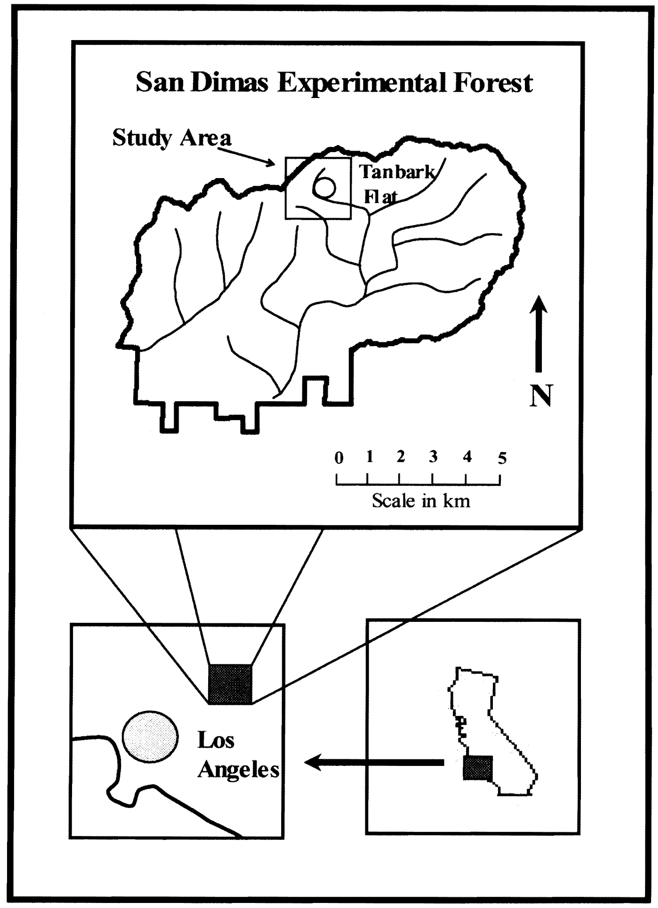


Figure 1 Location map of the San Dimas Experimental Forest.

Management treatments following a wildfire in 1960 involved the vegetation type-conversion of some native chaparral watersheds to a mixture of perennial grasses. Accompanied by herbicide spraying of the re-growing brush vegetation to assist in the grass establishment, these perennials included a variety of wheatgrass species (*Agropyron* spp.), Harding grass (*Phalaris tuberosa* var. *stenoptera*), big bluegrass (*Poa ampla*), smilo grass (*Oryzopsis miliacea*) and blando brome (*Bromus mollis*) (Corbett and Green, 1965).

In 1994, a study was initiated to quantify sediment fluxes through several small (1-3 ha) headwater catchments in the SDEF that last burned in the 1960 wildfire (Wohlgemuth, 1996). Because of differences in the nature of the ground surface vegetation, hillslope erosion was an order of magnitude less in type-converted grass watersheds compared to chaparral catchments. Sediment yield was virtually negligible for both vegetation types in the unburned watersheds. One of these chaparral watersheds was burned in a prescribed fire in 2001. First year post-fire hillslope erosion was twice as great as pre-burn levels during the dry season, and increased by 5-fold in the wet season, despite a record drought year. First-year post-fire sediment yield was 20 times greater than the unburned annual average (Wohlgemuth and Hubbert, in press).

In September 2002 virtually the entire SDEF burned in the Williams Fire, a high severity wildfire that consumed the vegetation on nearly 15,000 ha across the San Gabriel Mountains. The fire burned over the aforementioned sediment flux study, providing a unique opportunity to quantify hillslope erosion and small watershed sediment yield following a wildfire on the same sites for which there were extensive pre-fire measurements. The areas that burned in the 2001 prescribed fire did not re-burn in the 2002 wildfire.

## METHODS

In the sediment flux study, four small watersheds were selected to measure hillslope erosion: three in native chaparral vegetation and one in type-converted grass (Wohlgemuth, 1996). Hillslope erosion was sampled using sheet metal collector traps with a 30 cm aperture (Wells and Wohlgemuth, 1987). Seventy-five traps were placed on unbounded plots scattered throughout each watershed. The traps were installed in summer 1994. Sediment was collected for 8 years prior to the Williams Fire and through the third post-fire winter. One of the chaparral watersheds completely burned in the 2001 prescribed fire. Hillslope erosion is expressed as a flux: the air-dried mass of collected debris per unit width of slope contour (kg $m^{-1}$) per collection period. Although 26 sediment collections have been made to date at irregular intervals over the life of the project, the data are aggregated here into annual erosion periods.

Sediment was trapped and measured behind earth-filled dams constructed after the 1960 wildfire (Rice et al., 1965). Sediment yields were calculated using an engineering end-area formula (Eakin, 1939) based on repeated sag tape surveys of permanent cross sections (Ray and Megahan, 1978). Sediment yield was measured from 15 small watersheds: eight in native chaparral vegetation and seven in type-converted grass. The debris basins were re-activated in winter 1994. Sediment yield was measured for 8 years prior to the Williams Fire and through the third post-fire winter. Two watersheds completely burned in the 2001 prescribed fire, one from each vegetation type. Three watersheds partially burned in the prescribed fire and were discarded from post-fire analysis. Two watersheds were newly re-activated after the Williams Fire. See Table 1 for an accounting of the 17 small watersheds used in this study. To normalize for catchments of different sizes, comparisons in sediment yield were made as cubic meters per hectare. A centrally located weighing rain gage recorded precipitation amounts and intensities throughout the study period.

## RESULTS AND DISCUSSION

Results of the annual rainfall, hillslope erosion, and watershed sediment yield by hydrologic year (October to September) over the duration of the project are arrayed in Table 2.

**Rainfall**: Tabulated values show four years of average to above average precipitation, followed by six years of drought, followed by a very wet year (Table 2). During this study period, the SDEF experienced both the wettest (2005) and driest (2002) years in its 72-year history. Precipitation amounts and rainfall intensities are often related, and the 24-hour maximum generally correlates well with the annual totals. Conversely, the 15-minute maximum shows little relation with the annual amounts (Table 2).

Table 1 Listing of the sediment yield watersheds.

| Watershed ID | Area (ha) | Vegetation | Re-activated | Comments |
|---|---|---|---|---|
| 0505 | 2.49 | Brush | 2002 | Added after the Williams Fire |
| 0506 | 2.74 | Grass | 1994 | |
| 0507* | 3.25 | Grass | 1994 | |
| 0508* | 2.38 | Brush | 1994 | |
| 0512 | 1.95 | Brush | 1994 | Partial burn; discarded 2001 |
| 0513 | 3.21 | Grass | 1994 | Partial burn; discarded 2001 |
| 0514 | 3.28 | Grass | 1994 | Partial burn; discarded 2001 |
| 0516 | 2.04 | Grass | 1994 | |
| 0517 | 1.57 | Brush | 1994 | |
| 0519 | 2.27 | Grass | 1994 | Burn in prescribed fire 2001 |
| 0520 | 2.21 | Brush | 2002 | Added after the Williams Fire |
| 0541 | 0.76 | Brush | 1994 | |
| 0542* | 2.13 | Brush | 1994 | |
| 0550 | 1.28 | Brush | 1994 | |
| 0552 | 2.22 | Brush | 1994 | BAER treatment; discarded 2002 |
| 0554 | 3.12 | Grass | 1994 | |
| 0560* | 1.28 | Brush | 1994 | Burn in prescribed fire 2001 |

* Hillslope erosion watershed

Short bursts of intense rain often govern the erosion process (Moody and Martin, 2001). Unfortunately, the values for the 15-minute maximum have no relation to annual erosion (hillslope or small watershed) for either vegetation type before or after fire (Table 2). This is understandable on the hillsides, where much of the erosion in southern California steeplands is produced by the mechanism of dry ravel, in the absence of any rain (Wohlgemuth, 1996). Watershed sediment yield, which is strictly rainfall/runoff determined, is evidently related to a more complex relationship of amounts, intensities, and perhaps antecedent moisture conditions. While rainfall is a necessary driver, it appears that increased landscape sensitivity controls accelerated erosion in the post-fire environment.

**Hillslope Erosion**: Prior to burning, annual hillslope erosion was nearly an order of magnitude greater under brush vegetation compared to type-converted grass (Table 2), confirming previously published results (Wohlgemuth, 1996). However, in the post-fire environment, annual hillslope erosion was roughly equal for the two vegetation types (Table 2), although values were slightly greater in the burned chaparral watersheds. Presumably the fire removed the differential resistances to surface sediment transport, equalizing the erosion response for the two types of vegetation.

Table 2 Annual rainfall, hillslope erosion, and sediment yield over the duration of the study.

| **Hydrologic Year** | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rainfall (mm)** | | | | | | | | | | | |
| Total | 1227 | 688 | 738 | 1367 | 347 | 526 | 597 | 252 | 615 | 408 | 1848 |
| 24-hour maximum | 118 | 168 | 85 | 169 | 42 | 83 | 60 | 64 | 86 | 100 | 232 |
| 15-min maximum | 6 | 17 | 5 | 15 | 6 | 5 | 4 | 9 | 4 | 5 | 13 |
| **Average Hillslope Erosion (kg $m^{-1}$ $yr^{-1}$)** | | | | | | | | | | | |
| Unburned | | | | | | | | | | | |
| Grass (n=75) | 1.0 | 0.6 | 0.5 | 0.9 | 0.5 | 0.3 | 0.4 | 0.3 | - | - | - |
| Brush (n=225) | 6.0 | 6.0 | 4.4 | 6.0 | 3.9 | 4.7 | 3.2 | 1.8 | - | - | - |
| Prescribed Burn | | | | | | | | | | | |
| Brush (n=75) | - | - | - | - | - | - | 5.3 | 30.9 | 12.7 | 2.1 | 3.6 |
| Wildfire | | | | | | | | | | | |
| Grass (n=75) | - | - | - | - | - | - | - | - | 37.9 | 3.2 | 6.8 |
| Brush (n=150) | - | - | - | - | - | - | - | - | 53.6 | 4.9 | 9.8 |
| **Average Sediment Yield ($m^3$ $ha^{-1}$ $yr^{-1}$)** | | | | | | | | | | | |
| Unburned | | | | | | | | | | | |
| Grass (n=7) | 0 | 0 | 0 | 0.7 | 0 | 0 | 0 | 0 | - | - | - |
| Brush (n=8) | 0 | 0.8 | 0 | 2.8 | 0 | 0 | 0.5 | 0.2 | - | - | - |
| Prescribed Burn | | | | | | | | | | | |
| Grass (n=1) | - | - | - | - | - | - | - | 13.2 | 0 | 0 | 0 |
| Brush (n=1) | - | - | - | - | - | - | - | 31.3 | 6.3 | 1.6 | 0.8 |
| Wildfire | | | | | | | | | | | |
| Grass (n=4) | - | - | - | - | - | - | - | - | 23.3 | 0.3 | 3.9 |
| Brush (n=7) | - | - | - | - | - | - | - | - | 37.6 | 0 | 5.4 |

Hillslope erosion in the first-year post-fire was an order of magnitude greater than unburned levels in the brush watersheds, and nearly two orders of magnitude greater under the grass vegetation (Table 2), again reflecting the parity in post-burn response. In subsequent years post-fire, annual hillslope erosion declined dramatically in both vegetation types, attesting to the rapid recovery of the burned hillsides. In part this recovery can be attributed to the re-growing vegetation on the sites, but it also stems from the removal of the easily mobilized sediment from the hillsides and exposing less erodible soil material at the surface. The record rainfall in 2005 produced a modest increase in annual hillslope erosion (Table 2), suggesting a residual landscape sensitivity from the fire, especially in the grass vegetation.

Post-fire annual hillslope erosion on brush vegetation was similar for the prescribed burn and the wildfire (Table 2). The prescribed fire occurred in May 2001, after the rainy season had ceased. Adding the dry season erosion from 2001 to the annual totals for 2002 and 2003, the prescribed burn watershed had a sediment flux of nearly 49 kg $m^{-1}$, compared to a flux of 59 kg $m^{-1}$ for the first two years after the wildfire (Table 2). While the lower value in the prescribed fire watershed may result from lower fire severities, and hence less watershed disturbance, more probably this response reflects the record low rainfall following the prescribed burn (Wohlgemuth and Hubbert, in press). This is supported by the higher second-year erosion values for the prescribed burn watershed under a wetter year compared to the wildfire (Table 2).

**Sediment Yield**: Prior to burning, annual small watershed sediment yield was slightly greater under brush vegetation compared to grass, but virtually negligible for most years (Table 2). Presumably this reflects the greater sediment availability for channel transport during wet years because of the higher sediment delivery from the hillslopes under brush vegetation. In the post-fire environment this pattern continued, with the brush catchments generating moderately more annual sediment yield than the grass (Table 2). Again, this can probably be accounted for by greater sediment storage in the channels of the brush watersheds prior to the fire, and thus the greater availability for post-burn channel scour.

In the immediate post-fire year, watersheds of both vegetation types produced two orders of magnitude more sediment yield than the unburned annual average (Table 2). In part this reflects the accelerated hillslope erosion and sediment delivery to the channels, but the increased runoff from water repellent hillsides can also more effectively entrain sediment deposits already in the channels. In subsequent post-fire years, annual sediment yields decreased dramatically, mirroring the hillslope erosion recovery and a relatively rapid return to baseline levels (Table 2). No doubt the easily mobilized channel sediment was flushed out of the watersheds during the floods of the first post-fire year. The record rainfall in 2005 produced a moderate increase in annual sediment yield (Table 2), again suggesting a residual landscape sensitivity from the fire.

Post-fire annual sediment yield under both vegetation types was similar for the prescribed burn and the wildfire (Table 2). Care must be taken not to over-extrapolate these data from the single prescribed burn watershed for each vegetation type. For example, it appears from Table 2 that the inherent site factors of the prescribed burn grass catchment produced anomalously low values of sediment yield. However, the post-fire response over the first two years is virtually identical for the brush watersheds, both prescribed burn and wildfire, despite the differences in rainfall.

## CONCLUSIONS

In southern California steeplands, accelerated post-fire erosion is inevitable. A wildfire that burned over an ongoing sediment flux study revealed remarkably similar patterns of both hillslope erosion and small watershed sediment yield: a one to two order of magnitude increase in immediate post-fire erosion followed by a relatively rapid recovery to baseline levels. Annual erosion has little relation to peak rainfall intensities. Post-fire erosion response was very similar whether the watersheds burned in a prescribed fire or a wildfire. Although rainfall is a necessary driver, post-fire erosion is governed more by the landscape sensitivity to the agents of erosion.

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