HILLSLOPE EROSION AND SMALL WATERSHED SEDIMENT YIELD BEFORE AND AFTER FIRE IN SOUTHERN CALIFORNIA

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Abstract: In 2002, a wildfire burned over an ongoing sediment flux study in the steep, chaparral-covered foothills of the San Gabriel Mountains of southern California. The study area had previously burned in 1960. Southern California experiences a Mediterranean climate with cool wet winters and hot dry summers. Average annual rainfall for the study area is 714 mm (80-year record) with an average two-year 30-minute peak intensity of 29 mm hr^{-1}. Hillslope erosion was measured in 30 cm collector traps. These traps were serviced multiple times per year to distinguish wet season from dry season erosion. Small watershed (1-3 ha) sediment yield was measured behind earthen debris dams. Three of the study watersheds were in mixed chaparral vegetation and one was in type-converted grass. One of the chaparral watersheds was burned in a prescribed fire in 2001 and did not re-burn in the wildfire. Hillslope erosion and small watershed sediment yield data were collected for 7 or 8 years prior to burning then for 5 or 6 years following fire, including the complete post-fire erosion record. Continuous rainfall was measured in a centrally-located weighing bucket recording raingage. Rainfall, both totals and intensities, was generally below average during the study period, especially immediately after the fires. Prior to fire, hillslope erosion was considerable, was an order of magnitude less under grass vegetation compared to chaparral, dry season erosion was equal to wet season erosion in all watersheds, but sediment yield was only minor and associated with high rainfall years at the watershed scale. In the first post-fire year, both hillslope erosion and small watershed sediment yield increased by 1-2 orders of magnitude over pre-fire levels and all parts of the landscape responded similarly. Hillslope erosion rates and small watershed sediment yields returned to pre-fire levels and patterns within two to three years post-fire. The magnitude and patterns of erosion following a prescribe burn in chaparral was very similar to those following a wildfire, although the recovery curve was somewhat flatter after the prescribed fire. Future studies will test a variety of predictive models against the current dataset as a benchmark to evaluate their performance as a tool for planning and risk assessment in southern California chaparral watersheds.

INTRODUCTION

Fire has been a part of the southern California landscape since before recorded history and is the disturbance event which drives much of the environmental response in southern California (Sugihara and Barbour 2006). Chaparral and coastal sage scrub vegetation communities have adapted to periodic burning and some species may require fire in order to reproduce (Keeley 2006). Furthermore, fire drives much of the surface erosion experienced across the landscape. With the removal of both the vegetation cover and the protective layer of organic litter post-fire hillside slopes are initially susceptible to dry ravel erosion and subsequently to raindrop splash (Rice 1974). Fire also alters the physical and chemical properties of the soil – bulk density and water repellency – promoting surface runoff at the expense of infiltration (DeBano 1981). This enhanced post-fire runoff removes more soil material from the denuded hillsides and can mobilize sediment deposits in the stream channels to produce debris flows with tremendous erosive power (Wells 1987). Post-fire accelerated erosion eventually abates as the re-growing

vegetation canopy and root system stabilize the hillslopes and provides protection against the agents of erosion (Barro and Conard 1991). However, in the interim, wildfires coupled with heavy winter rains can produce floods and debris flows that threaten human life, property, and infrastructure (roads, bridges, utility lines, communication sites) far downstream from the burn area itself. This places an extra burden on land managers and hazard protection agencies that must be able to predict post-fire watershed response and mitigate against any potentially negative consequences to these values at risk.

Although the patterns of post-fire erosion 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. Prediction, usually in the form of numerical modeling, is only possible with a sufficient understanding of the quantitative effects of fire on erosion processes. Fortuitously, a wildfire on the San Dimas Experimental Forest burned over an ongoing sediment flux study and 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 or evaluate existing models of post-fire erosion for the southern California area.

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, and has been the site of extensive hydrologic monitoring for over 80 years (Dunn et al. 1988). Established in 1933, with its headquarters at Tanbark Flat (34° 12’ N latitude, 117° 46’ W longitude) the SDEF is located in the San Gabriel Mountains, about 45 km northeast of Los Angeles, California (Figure 1).

Elevations in the study area range from 750 to 1050 meters and topography consists of a highly dissected mountain block with steep-walled canyons and steep channel gradients. Bedrock geology in the SDEF is dominated by Precambrian metamorphics and Mesozoic granitics that produce shallow, azonal, coarse-textured soils (Dunn et al. 1988). The SDEF experiences a Mediterranean-type climate, characterized by hot, dry summers and cool, moist winters. Temperatures range from -8° C to 40° C. Mean annual precipitation, falling almost exclusively as rain, is 714 mm (80-year record), but rain during individual years can range from 252 to 1848 mm. Over 90 percent of the annual precipitation falls between the months of November and April (Wohlgemuth 1996). The two-year 30-minute peak rainfall intensity (an index of rainfall erosivity) for the study area is 29 mm hr^{-1} (Bonnin et al. 2011).

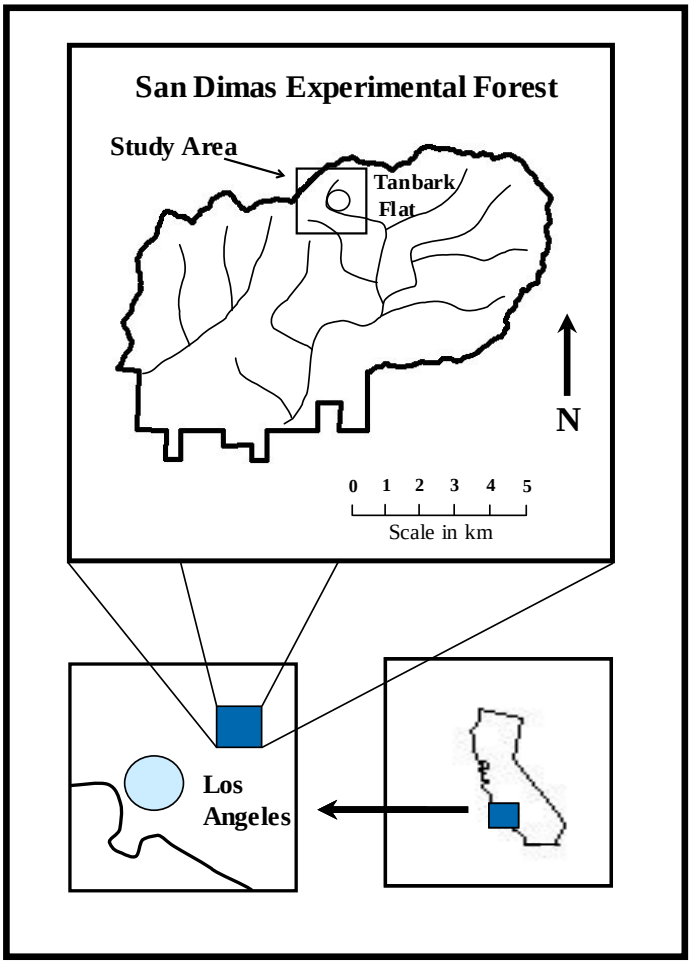

Figure 1 Location map of the San Dimas Experimental Forest.

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 black sage (*Salvia mellifera*). 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 2006). Fuel loadings of mature chaparral on the SDEF ranged from 110 to 135 Mg ha^{-1} (40-50 t ac^{-1}) (Ottmar et al. 2000). Management treatments following a wildfire in 1960 involved the vegetation type-conversion of some native chaparral watersheds to a mixture of perennial grasses. It was thought that type-conversion would aid in future fire control and would enhance water yield (Rice et al. 1965). To assist in the grass establishment, regenerating shrubs were sprayed with herbicides. These perennials included a variety of wheatgrass species (*Agropyron spp*.), Harding grass (*Phalaris tuberosa* var. *stenoptera*), big bluegrass (*Poa ampla*), smilo grass (*Piptatherum miliaceum*), veldt grass (*Ehrharta calycina*), and blando brome (*Bromus hordaceous*) (Corbett and Green 1965). By 2002, substantial amounts of buckwheat (*Eriogonum fasiculatum*) and

black sage had also established on the type-converted watersheds. Fuel loadings on the converted watersheds prior to the 2002 wildfire were 14-27 Mg ha^{-1} (5-10 t ac^{-1}) (Ottmar et al. 2000).

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). One of these chaparral watersheds was burned in a prescribed fire of moderate to high severity in 2001 (Wohlgemuth and Hubbert 2008). Following a winter drought and a hot, dry summer, almost all of the SDEF burned in a wildfire in late September 2002. A smoke plume that rose almost vertically indicated an absence of wind, which allowed the fire to burn relatively slowly, permitting longer fire residence times that resulted in substantial soil heating. In most parts of the SDEF, the fire burned at high severity, consuming all the aboveground biomass and leaving only the skeletons of the largest stems (Napper 2002). The areas that burned in the 2001 prescribed fire did not re-burn in the 2002 wildfire. Both fires burned over the aforementioned sediment flux study, providing a unique opportunity to quantify hillslope erosion and small watershed sediment yield following fire on the same sites for which there were extensive pre-fire measurements.

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 (Figure 2) with a 30 cm aperture (Wells and Wohlgemuth 1987). Seventy-five traps sampled unbounded plots on both vertical hillslope transects and at the slope/channel interface in each watershed. The traps were installed in summer 1994. Sediment was collected for 7 years prior to the prescribed burn and 8 years prior to the wildfire. Sediment collection continued through the fifth (wildfire) or sixth (prescribed burn) post-fire winter. Hillslope erosion is expressed as a yield: the air-dried mass of collected debris per square meter of potential contributing area normalized to an annual rate based on the length of the collection period (kg m^{-2} yr^{-1}). The median value from these sediment collectors was used as a measure of central tendency for comparisons. These traps were serviced multiple times per year to distinguish wet season hillslope erosion lasting approximately four months from dry season hillslope erosion lasting about eight months.

Sediment was also trapped and measured behind earthen dams (Figure 3) constructed after the 1960 wildfire (Rice et al. 1965). These debris basins were re-activated in winter 1994. 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 for 7 or 8 years prior to and 5 or 6 years following the prescribed burn or wildfire as described above. Sediment yield was normalized by contributing area to account for catchments of different sizes and aggregated to annual totals (m^3 ha^{-1} yr^{-1}).

A centrally located weighing raingage recorded precipitation amounts and intensities throughout the study period.

Figure 2 Hillslope erosion sediment collector trap.

Figure 3 Debris basin for trapping small watershed sediment yield.

RESULTS AND DISCUSSION

Rainfall: Rainfall is the ultimate driver of all hydrologic erosion, both on the hillside slopes and in the channels of ephemeral streams. Annual rainfall totals and peak 30-minute intensities for the duration of the study period are arrayed in Table 1. During this period, both the highest (1848 mm) and the lowest (252 mm) rainfall totals of the entire 80-year record were experienced. Generally, high annual totals correlated positively with peak 30-minute intensities, but there were some notable exceptions (Table 1). Of the 13 years of study, only four exceeded the annual average rainfall and only four exceeded average peak intensity. The prescribed burn was followed by the record low annual total but with a peak intensity slightly above average, while the wildfire was followed by a sub-normal annual total and a peak intensity that was only half the long-term average (Table 1).

Hillslope Erosion: Surface erosion yields from the collector traps are arrayed by watershed and season in Table 1. Prior to fire, hillslope erosion was considerably less under the type-converted grass vegetation than the native chaparral, as previously reported (Wohlgemuth 1996, 2006). This difference may be explained by the density of plant stems providing barriers to surface erosion: chaparral typically has a density of about 1 stem per square meter while the grass has a density of thousands of stems per square meter, creating a variable resistance to the processes of

erosion between the two vegetation types. Furthermore, the amount of dry season erosion and wet season erosion was roughly equal in the unburned condition (as opposed to their yields over unequal time spans as displayed in Table 1). The protection afforded by the plant canopies and extensive litter layers prevented surface runoff on the unburned hillsides except during the most intense rainstorms. Thus wet season hillslope erosion was muted on the unburned landscape, being no greater than ravel, the pervasive erosion process during the dry season (Rice 1974).

Table 1 Median (n=75) hillslope erosion yields (kg m^{-2} yr^{-1}) by watershed and season. I_{30} is peak 30 minute rainfall intensity. Watershed Chaparral 3 was burned in a prescribed fire one year prior to the wildfire. Numbers in italics are post-fire values.

			Watershed							
	Rainfall		Grass		Chaparral 1		Chaparral 2		Chaparral 3	
Year	Total (mm)	I_{30} (mm hr^{-1})	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1995	1227	20	0.02	0.05	0.28	0.64	0.32	0.67	0.20	0.45
1996	688	59	0.01	0.02	0.32	0.66	0.26	0.33	0.31	0.54
1997	738	18	0.01	0.01	0.30	0.47	0.26	0.35	0.28	0.36
1998	1367	53	0.04	0.02	0.34	0.48	0.36	0.43	0.44	0.42
1999	347	19	0.01	0.01	0.37	0.36	0.36	0.38	0.31	0.45
2000	526	16	0.01	0.01	0.26	0.49	0.33	0.40	0.28	0.40
2001	597	12	0.02	0.01	0.46	0.32	0.45	0.31	0.32	0.43
2002	252	33	0.02	0.01	0.33	0.16	0.29	0.22	*0.95*	*1.62*
2003	615	14	*0.18*	*4.68*	*1.41*	*8.70*	*0.74*	*5.12*	*0.34*	*0.95*
2004	408	17	*0.07*	*0.09*	*0.11*	*0.28*	*0.06*	*0.21*	*0.05*	*0.06*
2005	1848	49	*0.06*	*0.07*	*0.18*	*0.13*	*0.15*	*0.13*	*0.08*	*0.07*
2006	690	22	*0.05*	*0.02*	*0.20*	*0.14*	*0.15*	*0.08*	*0.16*	*0.06*
2007	277	17	*0.02*	*0.01*	*0.07*	*0.06*	*0.05*	*0.04*	*0.05*	*0.06*

In the first post-fire year, despite low rainfall totals (prescribed fire) or intensities (wildfire), yields of surface erosion increased by 1-2 orders of magnitude compared to pre-burn rates (Table 1), as the vegetative barriers were incinerated by fire and resistances to the forces of erosion were removed. Moreover, the pre-fire difference in yield between grass and chaparral vegetation disappeared, as fire eliminated any differential resistances among the vegetation types resulting in a very similar erosion response. However, in the immediate post-fire environment, wet season hillslope yield was substantially greater than dry season yield (Table 1), likely caused by the alterations in soil characteristics which affect post-fire hillslope hydrology and increased surface runoff (DeBano 1981).

In subsequent post-fire years the patterns of pre-fire surface erosion returned. Yield was once again greater under chaparral vegetation than under grass (Table 1), although the chaparral values were much smaller than in the pre-fire environment. Some of this reduction is likely due to the proliferation of re-growing near-surface vegetation (Barro and Conard 1991), but it could also reflect the loss of the easily mobilized sediment that exposed a less erodible material at the surface, effectively reducing the sediment supply (Wohlgemuth and Hubbert 2008). In addition, by the third post-fire year, dry season hillslope yields were greater than wet season yields (Table

1). This rapid return to pre-fire patterns suggests that recovery to hillslope erosion baseline levels can occur very quickly in this southern California locale.

Intuitively, wet season hillslope erosion should be related to rainfall. However, there is no discernable relationship between annual rainfall total or peak intensity and wet season hillslope erosion, either before or after fire (Table 1). This suggests that although rainfall is a necessary driver, hillslope sediment yield is governed more by the landscape sensitivity and differential resistances to the agents of erosion.

Small Watershed Sediment Yield: Sediment yield in the debris basins is arrayed by watershed in Table 2. Pre-fire watershed sediment yield was minor and associated with high rainfall years. More often than not, the annual sediment yield from these small watersheds was zero (Table 2). Prior to fire, watershed sediment yield was less in the grass vegetation than the chaparral (Table 2), presumably associated with the greater hillslope erosion, sediment delivery, and channel loading under the shrub vegetation. Immediately following fire, despite the low rainfall values, watershed sediment yields increased by 1-2 orders of magnitude over pre-fire levels (Table 2). Field observations confirmed both an extensive rill network, indicating the delivery of water and sediment from the burned hillsides, and channel scour of the existing in-channel deposits of stored sediment. Furthermore, first-year post-fire sediment yield from these small watersheds was roughly similar for both vegetation types, suggesting again the removal of differential resistances to promote a nearly equal erosion response. In subsequent post-fire years, watershed sediment yield was minor, associated with high rainfall, and greater in chaparral catchments compared to type-converted grass drainage basins. This very rapid return to pre-fire patterns of small watershed sediment yield again suggests that this environment can recovery very quickly to baseline conditions.

Table 2 Annual sediment yield (m^3 ha^{-1} yr^{-1}) by watershed. I_{30} is peak 30 minute rainfall intensity. Watershed Chaparral 3 was burned in a prescribed fire one year prior to the wildfire. Numbers in italics are post-fire values.

	Rainfall		Watershed			
Year	Total (mm)	I_{30} (mm hr^{-1})	Grass	Chaparral 1	Chaparral 2	Chaparral 3
1995	1227	20	0	0	0.63	0
1996	688	59	0	0	0	6.35
1997	738	18	0	0	0	0
1998	1367	53	0.71	1.66	5.45	3.72
1999	347	19	0	0	0	0
2000	526	16	0	0	0	0
2001	597	12	0	0	0	0
2002	252	33	0	0	0	*31.16*
2003	615	14	*32.19*	*11.26*	*24.87*	*2.11*
2004	408	17	*0.11*	*0*	*0.74*	*4.02*
2005	1848	49	*2.60*	*4.87*	*9.38*	*1.81*
2006	690	22	*0*	*0*	*0*	*0.58*
2007	277	17	*0*	*0*	*0*	*0*

Prescribed Fire Versus Wildfire: Prescribed burns are conducted under more moderate conditions of weather and fuel moisture to prevent an unplanned and costly fire escape. It is therefore generally assumed that the erosion response to a prescribed fire should be less than that from a wildfire (Loomis et al. 2003). However, for comparable chaparral-covered catchments in this study, the patterns of post-fire hillslope erosion and small watershed sediment yield are very similar: an immediate spike in sediment production followed by a quick return to baseline levels (Tables 1 and 2), perhaps suggesting that some threshold of landscape response is exceeded by all fire in these chaparral environments. The greater wet season hillslope erosion values following the wildfire compared to the prescribed fire (Table 1) can be explained by the total rainfall values but also by the time of burning. The prescribed fire burned in mid-May while the wildfire burned in late September. With initial heavy storms of the rainy season typically commencing in November or December, the areas of the prescribed fire had more time to heal, including some vegetation re-growth, than did the areas that burned in the wildfire. The prescribed-burn area was therefore better able to resist the hydrologic forces of winter storms than the freshly-burned hillsides after the wildfire. However, the prescribed fire has a slightly flatter recovery curve (2 years) than the wildfire (1 year), suggesting that the response to these two different types of fires is not identical (Table 1), perhaps reflecting the differences in rainfall totals and intensities.

A Benchmark for Post-fire Erosion Models: The value of this study is that it quantifies long-term hillslope erosion and small watershed sediment yield from the same plots and sites both before and after fire. As such, it provides a benchmark to evaluate the performance of predictive models of post-fire sediment yield from southern California chaparral environments. These models, which run the gamut from strictly empirical (Universal Soil Loss Equation; Wischmeier and Smith, 1978) to physically-based (Water Erosion Prediction Project; Laflen et al. 1991), are used by land management and hazard protection agencies to estimate the magnitudes of post-fire erosion events. Future work will involve the testing of a variety of predictive models against this dataset to evaluate their performance as a tool for planning and risk assessment in southern California chaparral watersheds.

SUMMARY

The timing and patterns of hillslope erosion and small watershed sediment yield were quantified when a prescribed fire and a subsequent wildfire burned over a sediment flux study, providing pre-fire and post-fire erosion values for the exact same sampling units, including the complete post-fire erosion record. The data suggest that, although there is not an exact correspondence, for this southern California chaparral locale erosion on the hillsides and the output from small catchments are remarkably similar: a 1-2 order of magnitude increase in immediate post-fire erosion over pre-fire yields followed by a relatively rapid recovery to baseline levels. Grass vegetation produced less erosion than comparable chaparral areas prior to fire, most likely because of differences in stem densities and channel loading, but these differences were erased immediately after fire and the landscape appeared to be eroding equally. Wet season hillslope erosion was especially enhanced following fire, most likely due to attendant changes in soil characteristics that promote overland flow. Although there appeared to be a relationship between rainfall and small watershed sediment yield, there seemed to be no association between wet

season hillslope erosion and either total rain or peak rainfall intensity. In chaparral vegetation the response to a prescribed fire was very similar to that of a wildfire, although there was a slightly flatter recovery curve following the prescribed burn, perhaps because of different rainfall patterns. This suggests that some threshold of landscape response is exceeded by all fire in these southern California chaparral environments.

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