Post-Fire Watershed Response at the Wildland-Urban Interface, Southern California

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Abstract

In southern California, the unrelenting urban expansion into neighboring uplands has created a wildland-urban interface that is increasingly difficult to manage. In September 2002, the Williams Fire burned the San Dimas Experimental Forest (SDEF), mostly at high severity. This event provided an opportunity to describe and analyze the impacts of fire and the historical management practice of type-conversion on post-fire runoff, sediment yield, soil water repellency, and vegetation recovery in chaparral ecosystems at the wildland-urban interface.

Results indicate that soil water repellency increased with depth, declined with time since fire, was inversely related to soil moisture, and was only slightly different with the two pre-fire vegetation types. Herbaceous grasses and forbs dominated the post-fire vegetation initially, but all watersheds are reverting back to their pre-fire plant communities. Bare ground declined with time since fire, primarily as the litter layer accumulated. Number of species per watershed was similar with the two pre-fire vegetation types, although the species composition was different. Comparisons revealed similar magnitudes of post-fire watershed response for both pre-fire vegetation types. Runoff was large in the first post-fire year despite only moderate rainfall. Runoff exceeded the measurement equipment during the record rainfall year of 2005. Sediment yield was large immediately after the fire but was negligible the following year. However, sediment yield was minor during the record rainfall year of 2005, suggesting that the supply of easily mobilized debris was depleted after the first post-fire winter. If there were any differences in fire behavior between the two vegetation types, the landscape exhibited nearly identical fire effects and watershed responses.

Summarizing results and their applications in an effective format remains the greatest challenge in communicating science to policy- and decisionmakers. For this project, the traditional technology transfer tools of written reports and symposia presentations were supplemented with field tours and a special workshop to which all local Federal, State, county, and municipal land mangers, hazard protection agencies, and political administrators were invited.

Keywords: fire response, runoff, sediment yield, vegetation regrowth, nonwettable soils, management implications

Introduction

The unrelenting urban expansion into neighboring uplands in southern California has created a wildland-urban interface that is increasingly difficult to manage. Fire increases flooding and accelerated erosion that can adversely affect natural resources and downstream human communities. Wildfires coupled with heavy winter rains can threaten life, property, and infrastructure (roads, bridges, utility lines, communication sites), placing an extra burden on land managers who must be able to predict post-fire watershed response and mitigate against any potentially negative consequences to values at risk.

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Fire is a major disturbance event in southern California environments that drives much of the surface erosion. The post-fire landscape is susceptible to dry season erosion (ravel) and raindrop splash with the removal of the vegetation cover (Rice 1974). Moreover, fire alters the physical and chemical properties of the soil (bulk density and water repellency) promoting surface runoff at the expense of infiltration (DeBano 1981). Post-fire water repellency (or nonwettability) has been shown to be spatially variable (Hubbert et al. 2006) and dependent on changes in soil moisture (Hubbert and Oriol 2005). The 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. Post-fire accelerated erosion eventually abates as the re-growing vegetation canopy and root system stabilizes the hillslopes and provides protection against the agents of erosion (Barro and Conard 1991).

In 1960 most of the San Dimas Experimental Forest (SDEF) burned in the Johnstone Fire. Following the fire, 25 small watersheds were instrumented with flumes and debris basins to measure runoff and sediment yield. The performance of selected mechanical and vegetative erosion control techniques—including type-conversion to perennial grasses—were evaluated against controls in these experimental catchments (Rice et al. 1965). In 2002 the SDEF burned again in the Williams Fire, including the area of this previous study that contained both type-converted and native chaparral watersheds. This second fire provided an opportunity to describe and analyze the impacts of fire and the historical management practice of type-conversion on post-fire runoff, sediment yield, soil water repellency, and vegetation recovery in chaparral ecosystems at the wildland-urban interface.

The San Dimas Experimental Forest

The SDEF is a nearly 7,000-ha research preserve administered by the U.S. Department of Agriculture Forest Service–Pacific Southwest Research Station and has been the site of extensive hydrologic monitoring for 75 years (Dunn et al. 1988). Established in 1933, the SDEF is located in the San Gabriel Mountains, about 45 km northeast of Los Angeles, CA (Figure 1). Elevations range from 450 to 1,700 m, 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).

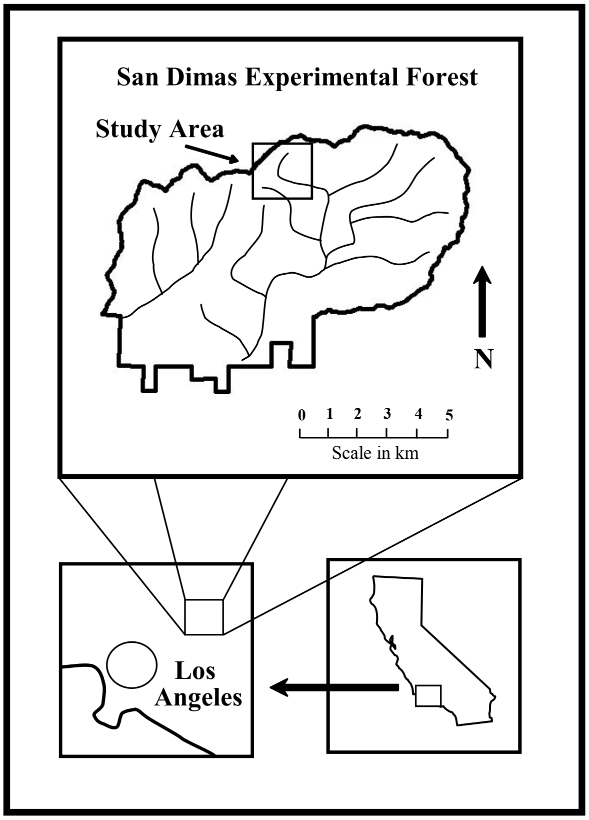

Figure 1. Location map of the San Dimas Experimental Forest.

The SDEF experiences a Mediterranean-type climate, characterized by hot, dry summers and cool, moist winters. Temperatures can range from -8°C to 40°C. Mean annual precipitation, falling almost exclusively as rain, is 714 mm (75-yr record), but rain during individual years can range from 252 to 1,898 mm. Over 90 percent of the annual precipitation falls between the months of November and April (Wohlgemuth 2006).

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). Pre-fire fuel loadings on the SDEF were 110–135 Mg ha^{-1} (40–50 t ac^{-1}) (Ottmar et al. 2000).

Management treatments following the Johnstone Fire 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*), 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. Pre-fire fuel loadings on the converted watersheds were 14–27 Mg ha^{-1} (5–10 t ac $^{-1}$) (Ottmar et al. 2000).

Following a winter drought and a hot, dry summer, the Williams Fire burned almost all of the SDEF in late September 2002. A smoke plume that rose almost vertically indicated an absence of wind, which allowed the fire to burn relatively slowly. The slow-moving fire permitted longer fire residence time that resulted in substantial soil heating. In most parts of the SDEF, the Williams Fire burned at moderate to high severity, consuming all the aboveground biomass and leaving only the skeletons of the largest stems (Napper 2002).

Methods

Following the 1960 Johnstone Fire, researchers selected replicate watersheds that were similar in size, shape, aspect, and potential erodibility. A trapezoidal flume to measure discharge and a debris basin to capture sediment was constructed in each catchment (Rice et al. 1965). Following the 2002 Williams Fire, we selected six of these small (1–3 ha) watersheds: three in native chaparral vegetation and three in type-converted grass. The stilling wells of the trapezoidal flumes were refurbished with a float and pulley water level recorder. The rating curves of the flumes were then used to compute flow discharge from stage height during the study period 2002–2006. 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) across the reservoirs. Surveys were conducted from 2002 to 2006. Precipitation was measured from throughout the study using the centrally-located SDEF master gage.

Vegetation was sampled for each of the six watersheds by first dividing each catchment into thirds (upper, middle, and lower sections). Three horizontal lines were randomly located across the entire watershed within each section. Ten 10-m line transects were randomly located along the horizontal lines in each section, yielding 30 transects per watershed. Plant cover by species was measured as centimeters covered along the 30 transects in each catchment. Vegetation was sampled from 2003 to 2006.

Soil water repellency was measured using the water drop penetration time (WDPT) method (Krammes and DeBano 1965). Twenty water drops were placed within a 30-cm-square area both at the mineral soil surface and at a depth of 2 cm. An additional 10 water drops were placed at a depth of 4 cm. Drop penetration time was measured with a stop watch and the times were aggregated to yield the following classification scheme: wettable, 0–5 seconds; slightly water repellent, 5–30 seconds; and moderate to highly water repellent, >30 seconds (Hubbert and Oriol 2005). Soil water repellency was measured twice a year, in late winter and in midsummer, from 2003 to 2006 repeatedly at 100 randomly chosen points within each pre-fire vegetation type. For every water repellency location, surface soil samples (0–5 cm) were taken in sealed tins and the ambient soil moisture was determined gravimetrically by oven drying (Gardner 1986).

Results

The soil water repellency testing produced a spectrum of results for each location. For comparison, the percentage of WDPT greater than 30 seconds was used to characterize water repellency at individual sites. Soil water repellency increased with depth and generally decreased with time since the fire (Table 1). Soil water repellency was also generally inversely related to soil moisture content (Table 1), exhibiting the seasonal fluctuations described by Hubbert and Oriol (2005). There appeared to be no clear relationships between soil water repellency and pre-fire vegetation type.

The study area was dominated by herbaceous plants (grasses and forbs) and bare ground for both pre-fire

Table 1. Rainfall, soils, vegetation, runoff, and erosion data by pre-fire vegetation and year.

Pre-fire vegetation	**Native chaparral**				**Type-converted grass**			
Year	**2003**	**2004**	**2005**	**2006**	**2003**	**2004**	**2005**	**2006**
Annual rainfall in millimeters[1]	615	408	1848	690	615	408	1848	690
Soil water repellency[2]								
Winter								
Surface	3	NA	1	1	3	NA	1	0
2 cm	6	NA	21	4	8	NA	8	7
4 cm	8	NA	22	6	10	NA	6	5
Summer								
Surface	12	2	3	7	10	4	12	3
2 cm	39	12	10	15	43	20	41	4
4 cm	53	17	21	25	53	22	42	15
Soil moisture content[3]								
Winter	13	NA	8	16	12	NA	8	14
Summer	1	1	2	2	1	1	1	1
Groundcover[4]								
Grass	1	3	<1	3	18	31	13	13
Forbs	48	46	5	12	30	12	2	2
Sub-shrubs	3	8	26	19	5	14	32	29
Shrubs	10	11	18	27	4	3	9	9
Litter	0	17	39	27	0	19	31	35
Bare ground	38	15	12	12	43	21	13	12
Number of species[5]	33	40	23	22	35	34	20	20
Peak discharge[6]	15	2	51[8]	<1	26	6	49[8]	1
Sediment yield[7]	43	0	6	2	32	0	5	0

[1] Average annual rainfall is 714 mm (75 years of record).
[2] Average percent of drop penetration times greater than 30 seconds. N=100.
[3] Average percent by volume. N=100.
[4] Average relative percent by watershed. Forbs are herbaceous plants other than grasses. Sub-shrubs are drought-deciduous, semi-woody plants. N=3.
[5] Average by watershed. N=3.
[6] Average cubic meters per second per hectare (times 100). N=3.
[7] Average cubic meters per hectare. N=3.
[8] Minimum values (runoff exceeded the limits of the measurement equipment).

vegetation types the first year after fire (Table 1). By the third year, both the herbaceous cover and the amount of bare ground declined, as woody vegetation (shrubs and sub-shrubs) grew and litter accumulated. On the type-converted watersheds, grasses rebounded initially then declined in favor of sub-shrub species, such as buckwheat and black sage. All watersheds appeared to be reverting back to their pre-fire plant communities. The number of species per watershed was nearly identical between pre-fire vegetation types (Table 1), declining over time as the herbaceous community faded away. However, the actual species composition on the two pre-fire vegetation types was different, although there was a good deal of overlap.

Post-fire watershed hydrologic response was measured by the normalized annual peak discharge ($m^3s^{-1}ha^{-1}$). The results of the first year's measurements show large peak discharges—somewhat larger in the type-converted grass vegetation—despite only moderate rainfall (Table 1). Not surprisingly, peak discharge was even greater during the record rainfall year of 2005. Furthermore, these are minimum values, as the runoff exceeded the limits of the measurement equipment during the largest storms. Peak discharge was negligible in 2006, despite the study area receiving more rain than in 2003.

Post-fire watershed erosion response was measured by the normalized annual sediment yields (m^3ha^{-1}). Results show that nearly all (85 percent) of the total sediment delivered to the debris basins over the course of the study came in the first year after the fire (Table 1). Slightly more sediment was generated by the native chaparral watersheds compared to those in type-converted grass vegetation. The record rainfall year of 2005 produced only minor erosion.

Discussion and Management Implications

Watershed conditions that would foster major runoff and erosion events in response to heavy rains include denuded hillsides and the presence of water repellent soils. These conditions were maximized during the first winter after the Williams Fire. In fact, large runoff and sediment yields were experienced on the SDEF in a year in which rainfall was only 86 percent of the long term average (Table 1).

Most of the sediment flushed out of these small watersheds over the duration of the study came in the first post-fire winter. This has huge implications for the establishment of emergency rehabilitation treatments. Whether on the hillslopes or in the stream channels, if mitigation measures are to be effective, they must be in place before the rainy season begins. However, their persistence or longevity after the first year appears to be considerably less critical.

The 2005 rainfall year was the wettest in 75 years of record keeping. The study area received more than an average year's worth of rain in one exceptional week. These storms produced tremendous runoff but generated only minor sediment yield. While the re-growing vegetation and accumulating litter layer had reduced the amount of bare ground to about 15–20 percent at the end of the previous growing season (Table 1), the watersheds would still be in a state of partial recovery only three years after the fire. An additional explanation is that the supply of easily-mobilized sediment was temporarily exhausted. Prior to the fire, sediment was delivered from the hillslopes to the ephemeral watercourses, where it accumulated in the channels. After the fire, more sediment was delivered to the channel networks, first by a pulse of dry ravel and then by overland flow with the onset of the winter rains (Wohlgemuth 2006). Soil water repellency enhances this runoff. Consequently, more water is conveyed more quickly off the hillsides and into the stream channels, where it mobilizes the loose sediments and carries them to the debris basins. This flushing event scoured the channels of the easily-transportable ash and fine sediment, and the filling process began anew. Hence, when the record floods occurred two years later, little loose sediment was available for transport. Therefore, we suggest that watershed erosion recovery after a fire is not solely a function of vegetation regrowth, but also relates to the supply of easily-mobilized sediment.

The two different pre-fire vegetation types had very different fuel loadings and fuel structures. Presumably this would influence the fire behavior (rate of spread and residence time), which would in turn govern the fire severity (degree of consumption and soil alteration) and ultimately dictate watershed response (runoff and erosion). However, whether or not there were any differences in fire behavior between the two vegetation types, the landscape exhibited nearly identical fire effects and watershed responses (Table 1). This suggests that watershed response in southern California is perhaps more related to the regional factors of topography, soils, and the disposition of rainfall than to fire characteristics. Alternatively, fire behavior on both vegetation types may produce fire effects that are beyond some threshold which governs watershed response.

Communicating Science to Decisionmakers

Summarizing results and their applications in an effective format remains the greatest challenge in communicating science to policy- and decisionmakers. Managers and administrators are usually too busy to peruse the scientific literature, cull the salient points, and derive the management implications. On the other hand, researchers do not do enough to publicize their science, especially as it relates to applied problems. For this project, the traditional technology transfer tools of written reports and symposia presentations were supplemented with field tours and a special workshop. An initial field tour was held in October 2003 at the beginning of the study to announce the project, demonstrate methodologies, and get feedback from the attendees. A special workshop devoted to presenting the results and management implications, along with an accompanying field tour, was held in May 2006. An invitation list was assembled that included all local Federal, State, county, and municipal land managers, hazard protection agencies (fire, flood control, public works), and political administrators who may have had even a remote interest in the project. Transportation from a central location and lunch were provided at no cost to the attendees. Although attendance at these events was less than we hoped (approximately 40 people each), the interaction and opportunities for one-on-one dialog was immensely satisfying to both the attendees and the conveners. This method of knowledge transfer proved to be an effective tool for both communicating science to decisionmakers and building professional relationships.

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References

Barro, S.C., and S.G. Conard. 1991. Fire effects on California chaparral systems: An overview. Environment International 17:135–149.

Corbett, E.S., and L.R. Green. 1965. Emergency revegetation to rehabilitate burned watersheds in southern California. U.S. Department of Agriculture, Forest Service, Research Paper PSW-22.

DeBano, L.F. 1981. Water repellent soils: A state-of-the-art. U.S. Department of Agriculture, Forest Service, General Technical Report PSW-46.

Dunn, P.H., S.C. Barro, W.G. Wells II, M.A. Poth, P.M. Wohlgemuth, and C.G. Colver. 1988. The San Dimas Experimental Forest: 50 years of research. U.S. Department of Agriculture, Forest Service, General Technical Report PSW-104.

Eakin, H.M. 1939. Instructions for reservoir sedimentation surveys. In H.M. Eakin, ed., Silting of Reservoirs, pp. 153–164. U.S. Department of Agriculture, Technical Bulletin 524.

Gardner, W.H. 1986. Water Content. In A. Klute, ed., Methods of Soil Analysis, pp. 493–544. American Society of Agronomy, Agronomy Monograph 9. Soil Science Society of America, Madison, WI.

Hubbert, K.R., and V. Oriol. 2005. Temporal fluctuations in soil water repellency following wildfire in chaparral steeplands, southern California. International Journal of Wildland Fire 14:439–47.

Hubbert, K.R., H.K. Preisler, P.M. Wohlgemuth, R.C. Graham, and M.G. Narog. 2006. Prescribed burning effects on soil physical properties and soil water repellency in a steep chaparral watershed, southern California, U.S.A. Geoderma 130:284–298.

Krammes, J.S., and L.F. DeBano. 1965. Soil wettability: A neglected factor in watershed management. Water Resources Research 1:283–286.

Napper, C. 2002. BAER Report, Williams Fire. U.S. Department of Agriculture, Forest Service, Angeles National Forest, FS-2500-8.

Ottmar, R.D., R.E. Vihnanek, and J.C. Regelbrugge. 2000. Stero photo series for quantifying natural fuels, vol. IV: Pinyon-juniper, chaparral, and sagebrush types in the Southwestern United States. PMS 883. National Wildfire Coordinating Group, Boise, ID.

Ray, G.A., and W.F. Megahan. 1978. Measuring cross sections using a sag tape: A generalized procedure. U.S. Department of Agriculture, Forest Service, General Technical Report INT-47.

Rice, R.M. 1974. The hydrology of chaparral watersheds. In Proceeding of a Symposium on Living with the Chaparral, Riverside, CA, 30-31 March 1973, pp. 27–34. Sierra Club, San Francisco, CA.

Rice, R.M., R.P. Crouse, and E.S. Corbett. 1965. Emergency measures to control erosion after a fire on the San Dimas Experimental Forest. In Proceedings of the Federal Inter-Agency Sedimentation Conference, 28 January–2 February 1963, pp. 123–130. U.S. Department of Agriculture, Miscellaneous Publication 970.

Wohlgemuth, P.M. 2006. Hillslope erosion and small watershed sediment yield following a wildfire on the San Dimas Experimental Forest, southern California. In Proceedings of the Eighth Federal Interagency Sedimentation Conference, 2-6 April 2006, Reno, NV, pp. 41–48. Advisory Committee on Water Information, Subcommittee on Sedimentation.