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Effects of hydromulch on post-fire erosion and plant recovery in chaparral shrublands of southern California

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Abstract. Following the Cedar Fire (one of seven large wildfires that burned in southern California during the autumn of 2003), aerial hydromulch was applied at 50 and 100% cover to reduce hillslope erosion in chaparral shrublands. Our objectives were to determine the effectiveness of hydromulch in preventing erosion, and to see if plant recovery was hindered by treatment. We installed 54 silt fences to measure sediment production. Five 1-m^2 grids were placed behind each fence to measure plant recovery. Hydromulch was effective in reducing erosion immediately after the fire; however, its benefits appeared to be limited to the first 2–4 months following fire, raising doubts as to its overall cost-effectiveness. The rapid breakdown of the hydromulch during the first 6 months after the wildfire provided little hillslope protection during the above-average October 2004 storm events. During the October events, both rainfall amount and storm intensity played a role in the magnitude of sediment production. Hydromulch did not affect post-fire plant recovery, with plant cover measuring >60% at all sites less than 2 years following the wildfire. Accelerated growth of chamise and forbs was likely due to hydromulch prolonging soil moisture retention. Large accumulations of dead litter following die-off of the herbaceous species could increase dry fuels, thus promoting wildfire and therefore shortening the fire return interval.

Additional keywords: Cedar Fire, chaparral, gabbro, granite, morning glory, silt fence.

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Introduction

Wildfires are a common occurrence in shrubland ecosystems associated with Mediterranean-type climates, which are distributed over five regions of the world including parts of California, central Chile, South Africa, Australia and the Mediterranean Basin. Nevertheless, fire effects, ecosystem recovery rates and magnitude of erosion events can be highly variable depending on fire extent and severity, lithology and topography, soil type, location and aspect, and intensity and amount of rainfall (Kutiel and Inbar 1993; Cerda and Lasanta 2005; Moody *et al.* 2008; Robichaud *et al.* 2008; Blake *et al.* 2009). In southern California and elsewhere, there is usually a first-year flush of erosion and sediment loss following wildfire, which can remain elevated for 3–10 years (Rowe *et al.* 1954; Florsheim *et al.* 1991; Wohlgemuth *et al.* 1998; Pierson *et al.* 2008). Major factors driving erosion in chaparral ecosystems include: loss of cover through foliage and litter consumption (Wohlgemuth *et al.* 1999), loss of soil structure resulting in loose, easily detachable soil (Kutiel and Inbar 1993; Hubbert and Oriol 2005), reduced interception and exposure of bare soil to rainsplash (Farres 1987), surface sealing and pore clogging (Larsen *et al.* 2009), and soil water repellency (DeBano 1981; Doerr *et al.* 2006). In chaparral ecosystems, much of the reduction in soil infiltration due to repellency is minimised because of the high variability in the spatial distribution of soil water repellency on the landscape (Coelho *et al.* 2004; Hubbert *et al.* 2006; Spigel and Robichaud 2007), and the reduction or disappearance of repellency properties at soil moisture thresholds ranging from 10 to 13% for areas mapped at low severity (Dekker *et al.* 2001; MacDonald and Huffman 2004; Hubbert and Oriol 2005).

Saturation overland flow, infiltration excess and dry ravel are additional key factors involved in post-fire erosion of chaparral ecosystems. Most chaparral ecosystems in southern California are noted for their shallow soils and steep slopes. When the water storage capacity of the regolith is exceeded, saturation overland flow occurs (Anderson and Burt 1990). Antecedent moisture conditions affecting the regolith water-storage capacity play an important role in initiating both overland and subsurface flows. When aboveground biomass is removed by fire, loss of soil moisture by transpiration is greatly reduced, therefore allowing near soil saturation to be reached much sooner during rain events (National Wildfire Coordinating Group 2001). Infiltration excess occurs when rainfall intensity exceeds the soil infiltration rate (Horton 1945). Dry erosion or ravel is the unconsolidated flow of soil material under the influence of gravity (Rice 1974). When slopes exceed ~50–60%, any disturbance can initiate the downward movement of ravel (Krammes 1960). In parts of southern California, dry ravel can account for over half of all hillslope erosion (Krammes 1969; Rice 1982).

Aerial hydromulch was developed and used initially for erosion control on roadcut and construction sites (Caltrans 2003). In burned areas bordering the wildland–urban interface, aerial hydromulch has become an important and popular treatment to stabilise steep hillslopes in high-profile areas. Hydromulch can decrease sediment production by: (1) providing cover on burned hillslopes (Napper 2006); (2) reducing raindrop impact erosion (Caltrans 2003); (3) reducing runoff during precipitation events by increasing infiltration into the soil (Debats *et al.* 2008); and (4) increasing soil water-holding capacity by decreasing soil evaporation (Vallejo *et al.* 2006). Additionally, hydromulch is preferable to dry straw mulch in areas prone to strong winds. Because of its high application and material costs, the cost-effectiveness of aerial hydromulch has been questioned when compared with values at risk. Hydromulch application costs are very high, if not the highest of all hillslope treatment options. For example, 270 ha of the Angora Fire near Lake Tahoe, CA, were treated in 2007 at \$US7932 ha^{-1} for a total cost of \$US2 141 070 (Weaver *et al.* 2007); 502 ha were treated on the Santiago Fire in Orange County, CA, at \$US9909 ha^{-1} for a total of \$US4 976 500 (Westmoreland 2007); and 194 ha were treated on the Griffith Park Fire at \$US10 297 ha^{-1} for a total of \$US2 000 000 (City of Los Angeles 2007). In comparison, the cost of straw mulch dropped from helicopter following the Schultz Fire in Flagstaff, AZ, was \$US1482 ha^{-1} and seeding was \$US161 ha^{-1} (Steinke 2010).

California chaparral consists of shrubs, herbs and grasses that commonly inhabit steep terrain and shallow soils at elevations ranging from 300 to 1500 m. Many chaparral wildland soils have low nutrient status and water-holding capacity (Neary *et al.* 2005), such that a hydromulch organic layer may promote a more favourable growing environment over the longer term. Substantial seedling establishment of herbaceous annuals and perennials, such as morning glory (*Calystegia macrostegia*), goldenfields (*Lasthenia californica*) and catseye (*Cryptantha* spp.), occurs during the first years following fire (Keeley *et al.* 1981). These species can provide fine fuels for the spread of wildfires. Much of the shrub component is composed of obligate resprouters (e.g. chamise (*Adenostoma fasciculatum*)) that resprout quickly following fire from belowground lignotubers high in nutrients and water (Keeley and Zedler 1978). Older, closed shrubland canopies inhibit establishment of invasive species, such as red brome (*Bromus madritensis* subsp. *rubens*), and the shallow seeds of the invasive grasses are often destroyed during wildfire (Keeley 2001).

Risk of post-fire erosion is particularly high at the expanding wildland–urban interface, where the chaparral provides excellent erosion protection and hillslope stabilisation. Fire greatly alters the physical characteristics of the landscape (Shakesby and Doerr 2006), which can dramatically increase runoff and erosion from fire-consumed watersheds (Kraebel and Sinclair 1940). Hydromulch treatments are prescribed at varying cover rates to limit soil erosion from these systems. However, few studies have evaluated the effectiveness of aerial hydromulch in reducing post-fire erosion, and its effects on plant response and recovery. Our overall objective was to quantify post-fire hillslope erosion in response to aerial hydromulch treatments. Specific objectives were (1) to compare hillslope erosion response at different hydromulch cover percentages; (2) to compare erosion between the gabbro and granitic soils; and (3) to determine the effects of aerial hydromulch on individual species recovery and percentage plant cover over time. Results from this research will help resource and watershed managers select appropriate post-fire treatments that are effective in reducing erosion and that leave little or no footprint on the environment.

Materials and methods

Site description

Wildfires in southern California fanned by Santa Ana winds burned 292 098 ha during a 2-week period of the autumn of 2003. The Cedar Fire, ignited on 25 October 2003 and completely controlled by 5 December 2003, was just one of seven large fires burning at this time. It consumed 113 424 ha NE of San Diego, CA, destroyed ~2700 residences and claimed 15 lives (Frazier 2003; Fig. 1). Although most of the chaparral systems burned rapidly as a crown fire, residence time was long enough for the fire to consume most of the standing biomass and litter layer, leaving only shrub skeletons and a mixture of ash and disturbed soil on the surface. A powerful Santa Ana offshore wind event occurred 2 weeks after the fire and removed much of the ash from the burned area, redistributing it out over the ocean. Burn severity mapped by the Burned Area Emergency Response (BAER) teams was 8% low, 78% moderate and 13% high on Forest Service lands. No water repellency was noted on any of the land surface (Frazier 2003). Repellency was not measured at any depth below the soil surface (Frazier 2003). Climate is Mediterranean and is characterised by winter cyclonic storms and hot, dry summers with rare summer convective storms. Average annual precipitation for the study area is 415 mm. Elevation ranged from 500 m at the granitic sites to 700 m at the gabbro sites. Because of loss of plant cover and a high percentage of bare soil, hillslope erosion leading to undesirable sediment loss and potential flood damage of downslope communities was anticipated.

To protect the community of Peutz Valley, aerial hydromulch was applied by helicopter (Fig. 2) to 445 ha of adjacent watersheds in order to reduce peak flood events and sediment yield downstream (Frazier 2003). The 445-ha hydromulch treatment was located ~8 km NE of Alpine, CA, (47 km NE of San Diego) near the upper portions of both the Peutz Valley and Capitan Grande Reservation watersheds that lie below Viejas Mountain. Treatment was planned to provide 50% cover on Forest Service land and 100% cover on portions of the Viejas Indian Reservation.

Geology, soils and vegetation

The lower portion of the treated area is underlain by granitic rocks of the Peninsular Range batholith, and gabbroic rock forms the upper watershed and lower slopes of Viejas Mountain (Todd 1978). Gabbro is a dark, large-crystal igneous rock that weathers slowly and is more resistant to erosion than granitic rocks. Areas of gabbro are marked by an abundance of cobble and stones on the surface. Because gabbroic rocks are mafic,

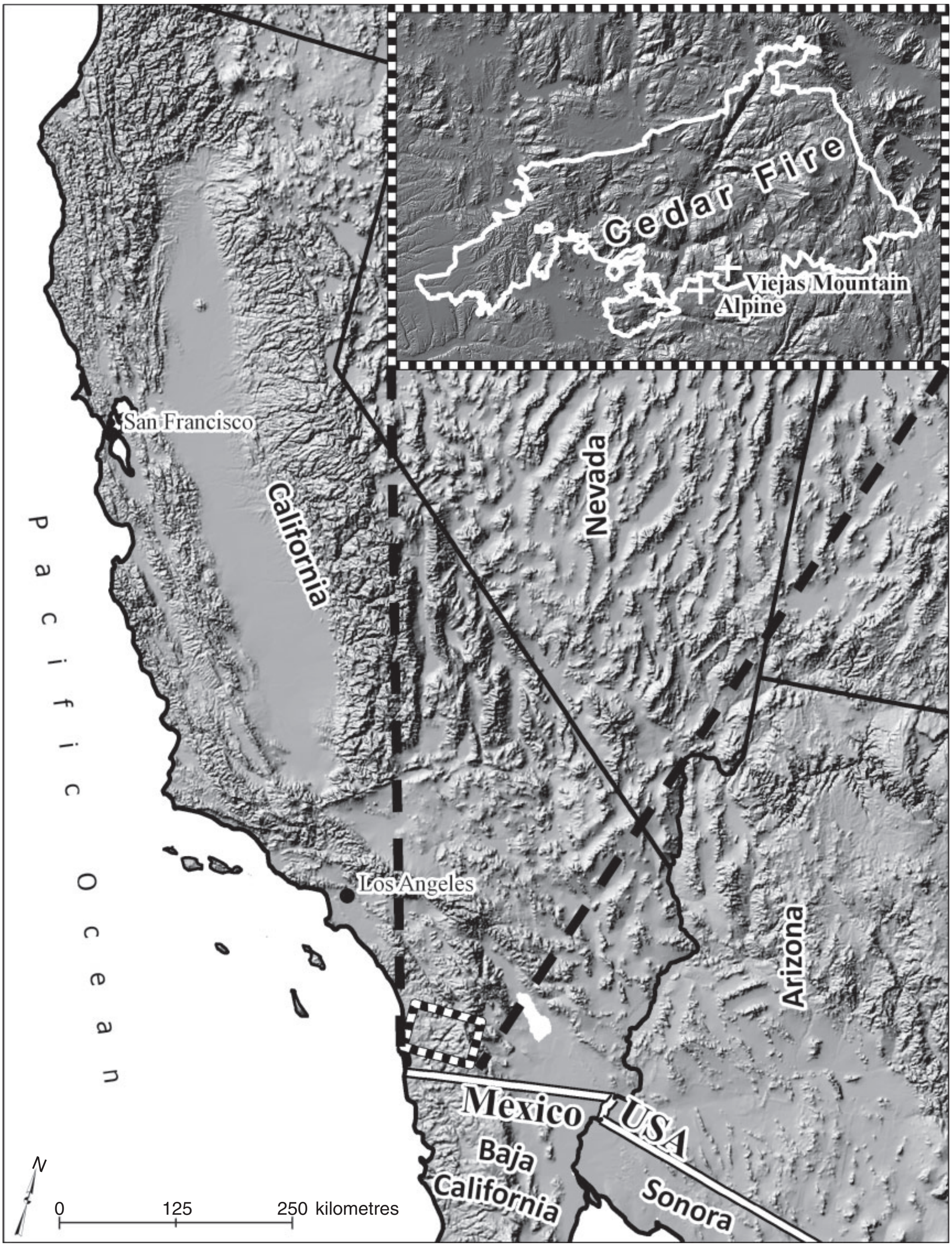

Fig. 1. Map showing the location of study site in relation to the Cedar Fire.

containing magnesium and iron-bearing minerals, weathering of the rock produces deep, reddish soils as compared with the light-brown granitic soils (Allinger 1979). Soil textures range from loamy sand (granitic parent material) to sandy loam (gabbro parent material). Soil infiltration rates range from 15 to 25 mm h^{-1} for loamy sand soil textures and 10 to 20 mm h^{-1} for sandy loam soil textures. Soil depths range from 50 to 80 cm on the granitics and from 40 to 90 cm on the gabbro parent material. Slope average was 27% on the gabbro sites, slightly steeper than the granitic sites, which were 18%. Soils mapped on the granitic terrain were of the Cieneba series (coarse-loamy, mixed, non-acid, thermic, shallow Typic Xerorthents), and soils formed

Fig. 2. Photos showing the aerial application of hydromulch at the base of Viejas Mountain and a constructed silt fence.

from gabbro rock were of the Las Posas series (fine, montmorillonitic, thermic Typic Rhodoxeralfs) (Brown 1973).

Common resprouting chaparral species found at the study site include: chamise, mission manzanita (*Xylococcus bicolor*), Eastwood manzanita (*Arctostaphylos glandulosa* Eastw.), sugar bush (*Rhus ovata* S. Watson), scrub oak (*Quercus berberidifolia* Liebm.), chaparral yucca (*Yucca whipplei*) and redberry buckthorn (*Rhamnas crocea*). Common forbs include morning glory, shortpod mustard (*Hirschfeldia incana*), deerweed (*Lotus scoparius*), goldenfields and catseye. Fire history before 2003 is unknown, but unburned pockets of chaparral appeared to be >40 years in age.

Aerial hydromulch

The aerially applied hydromulch (Fig. 2) was a bonded-fibre matrix (BFM) made up of ~40% shredded wood and 60% paper with a guar gum-based non-water-soluble tackifier (Hubbert 2006). The mulch is reported to be able to penetrate into and bond with the soil substrate to ~1.3-cm depths (Caltrans 2003). It can provide a thicker cover than ordinary hydromulch, and is recommended for steeper ground and areas frequented by high-intensity storms. Aerial hydromulch was applied during the second and third weeks of December 2003 by helicopter on 445 ha at a cost of US\$3705 ha^{-1} for a total of US\$1 650 000 (Hubbert 2006). The mulch was mixed as a slurry, and applied by helicopter at 50% cover to contributing watersheds of USDA Forest Service lands and at 100% cover on watersheds of the Viejas Indian Reservation. The 50% cover was placed on the contour at 30-m intervals (a 30-m strip with a 30-m gap in between).

Field measurements

We installed a total of 54 silt fences at the site with completion on 24 January 2004. We monitored both the 50 and 100% hydromulch treatments. In addition, we compared the treatments on two different parent materials, granite bedrock and gabbro bedrock. Silt fences were distributed as follows: gabbro control (Control-GA) = 13; gabbro 50% treated (GA-50) = 11; granitic control (Control-GR) = 10; granitic 50% treated (GR-50) = 10; and granitic 100% treated (GR-100) = 10. Controls were placed in areas without hydromulch but with comparable characteristics of geology, soils, topography, burn severity and prefire vegetation. Silt fences were made of synthetic woven geotextile fabric that allowed water but not sediment to pass. Construction of the silt fences followed guidelines provided by Robichaud and Brown (2002).

Silt fences were oriented across the contour perpendicular to the lines of potential runoff. A 1.5-m collecting area upslope of the silt fence was smoothed of any rocks or uneven spots, and a layer of construction chalk was then applied to mark the boundary of the natural soil and any subsequent accumulated sediment (Fig. 2). The contributing area was limited to a distance upslope of 30.5 m so the structure was not overtopped. In cases where we encountered a natural boundary, the measured length to the obstruction was used. A hand-dug trench (diagonal to the contour) was located at the uphill edge of the plot to collect eroded sediment coming from above the plot and divert runoff beyond the side edges of the plot. Because a majority of the Cedar soil sediments were coarse-textured, ranging from 0.2 to 0.8 mm, we believed silt-fence trapping efficiency would be higher than the >90% efficiencies reported by Robichaud *et al.* (2001) on both a storm-by-storm basis and a seasonal basis. Criteria for selection of sites for silt fence installation were (1) fairly uniform hillslope facets that avoided swales and interfluves, (2) being accessible by road, and (3) being similar in slope and representative of the overall landscape.

After rain events, sediment fences were cleaned out twice during the first winter and spring following the fire (on 3 March 2004 and 17 May 2004), during the second winter (3 December 2004) and in late and early summer of the two following years (18 August 2005 and 26 June 2006). Sediment weight was corrected for soil moisture content. Because contributing areas differed in area, sediment values were normalised.

Tipping-bucket rain gauges with data loggers were installed at each of the two study sites (granite parent material and gabbro parent material) and collected rain data from 1 February 2003 to 31 December 2006. Total rainfall duration, amount and the 10-, 30- and 60-min maximum rainfall intensities (I10, I30 and I60) were calculated for each rain event. Rain events were separated

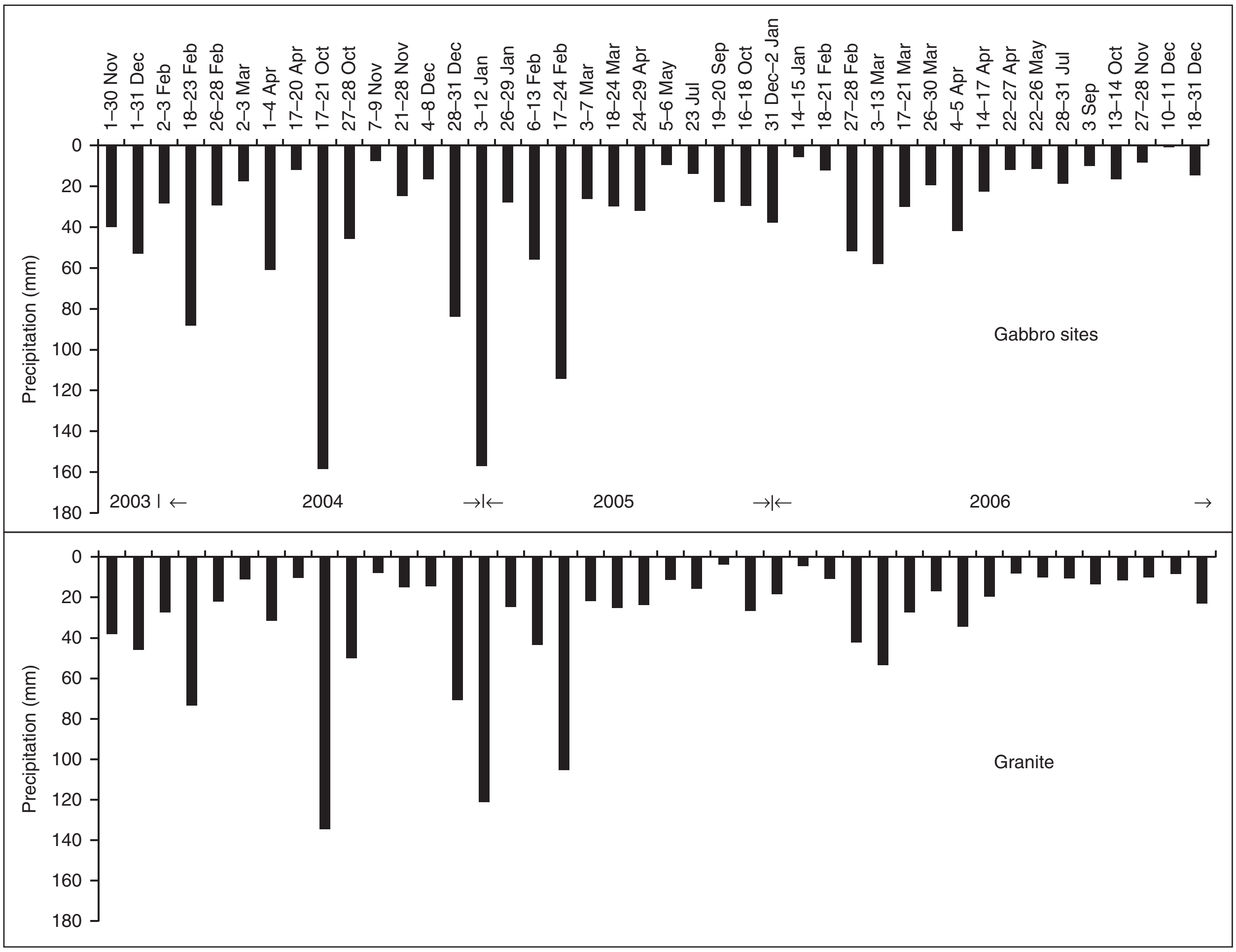

Fig. 3. Precipitation measurements were collected from 1 November 2003 to 31 December 2006. Rain gauges located at the gabbro and granitic sites were used to collect data from January 2004 through December 2006. Rainfall amounts from 1 November to 31 December 2003 were determined using data from the remote automated weather stations (RAWS) weather station located at Alpine, CA. Dates represent rain events that were either continuous, or consisted of two events (21–28 November, 4–8 December, 6–13 February, 22–27 April, 22–26 May, 18–21 December).

by a 24-h period with no rainfall, with the exception of the following dates: 21–28 November, 4–8 December, 6–13 February, 22–27 April, 22–26 May and 18–31 December, where two or more individual rain events were combined. Rainfall amounts from 1 November 2003 to 31 January 2004 were determined using data from the remote automated weather stations (RAWS) weather station located at Alpine, CA.

Plant cover including individual species was measured on 18 February 2004, 7 June 2004, 7 August 2005 and 27 June 2006. We positioned line transects along the right and left boundaries of the contributing area for each of the 54 silt fences. A total of five 1-m^2 grids were placed along transects behind each silt fence. The grids were located at 5, 15 and 25 m (left) and at 10 and 20 m (right) along the contributing area boundaries. At each sampling point, we placed a 1-m^2 frame on the surface that was separated into one hundred 10-cm^2 grids. Percentage cover measurements were taken using the pin-drop method at the 100 points. Individual plants were identified and recorded by genus and species and differentiated between grass, forbs and shrub. The following sampling criteria were used to record the type of cover within each grid: bare soil, rock (<7.5 cm in width), rock (>7.5 cm), plant cover, stump, downed wood (<2-cm diameter), downed wood (>2-cm diameter), litter and hydromulch treatment. The pin-drop recorded the first item contacted; therefore, the percentage rock cover decreased as new plant growth covered the rock.

Results

Aerial hydromulch

Treatment prescriptions called for aerial hydromulch to be applied at 50 and 100% coverages. Precipitation measured 121 mm between hydromulch application and the first sampling date (18 February 2004) (Fig. 3). It appeared that these rain events resulted in rapid erosion of the hydromulch. Hydromulch coverage on 18 February 2004 averaged only 55.8% for the GR-100 treatment, 26.9% for the GR-50 treatment and 20.2% for the GA-50 treatment, far below the targeted 50 and

Table 1. Percentage cover of treatment (hydromulch), litter, rock, shrub, forb, grass, total plant and total plant plus treatment coverage measured on control, 50 and 100% treatment for both gabbro and granitic parent materials on 18 February 2004, 7 June 2004, 5 July 2005 and 27 June 2006

Percentage cover for five selected species is also included. Control-GA = Gabbro control; GA-50 = 50% treated gabbro; GR-50 = 50% treated granitic; GR-100 = 100% treated granitic; Control-GR = Granitic control. Plant type or species determination were not made on the 18 February 2004 sampling date

Cover type	Control-GA				GA-50				GR-50				GR-100				Control-GR			
	18-Feb-2004	7-Jun-2004	5-Jul-2005	27-Jun-2006	18-Feb-2004	7-Jun-2004	5-Jul-2005	27-Jun-2006	18-Feb-2004	7-Jun-2004	5-Jul-2005	27-Jun-2006	18-Feb-2004	7-Jun-2004	5-Jul-2005	27-Jun-2006	18-Feb-2004	7-Jun-2004	5-Jul-2005	27-Jun-2006
Treatment	0.2	0.0	0.0	0.0	19.9	4.7	0.0	0.0	26.9	9.2	0.0	0.0	55.8	20.2	0.0	0.0	0.0	0.0	0.0	0.0
Litter	5.0	6.9	5.9	10.0	3.3	8.5	5.8	21.0	1.7	6.4	7.7	17.8	1.7	6.7	12.3	14.8	5.8	7.4	10.0	12.5
Rock (>7.5 cm)	14.4	11.7	7.0	8.6	22.8	23.1	12.8	14.7	0.1	0.1	0.2	0.9	0.6	0.0	0.0	0.0	0.2	0.2	0.1	0.1
Shrub	–	12.0	26.4	37.8	–	4.4	12.8	21.3	–	6.1	23.2	38.3	–	11.4	34.0	42.8	–	8.5	23.7	41.5
Forb	–	7.9	41.6	22.3	–	15.1	55.3	26.5	–	8.1	36.4	7.6	–	8.6	38.8	21.8	–	11.2	35.0	11.0
Grass	–	0.0	3.3	1.3	–	0.2	6.1	3.3	–	0.0	9.1	0.5	–	0.0	1.1	0.8	–	0.2	2.3	0.5
Total plant cover	10.4	19.0	70.0	61.1	8.3	19.6	71.9	51.1	5.4	13.3	69.3	46.1	6.4	19.7	74.3	64.6	8.7	18.0	60.7	53.0
Plant cover + treatment	10.6	19.0	70.0	61.1	28.2	24.3	71.9	51.1	32.3	22.5	69.3	46.1	62.2	39.9	74.3	64.6	8.7	18.0	60.7	53.0
Selected taxa																				
Adenostoma fasciculatum	–	3.9	10.2	16.2	–	2.4	7.3	14.2	–	2.8	17.4	19.8	–	6.4	27.2	37.6	–	1.9	13.2	21.6
Bromus madritensis rubens	–	0.0	3.3	1.2	–	0.2	5.7	3.1	–	0.0	9.0	0.3	–	0.0	1.1	0.8	–	0.2	2.3	0.5
Calystegia macrostegia	–	2.5	18.2	6.3	–	9.6	30.2	8.3	–	0.5	3.1	0.1	–	0.1	1.2	0.1	–	0.0	0.0	0.0
Cryptantha spp.	–	0.0	6.1	0.0	–	0.0	1.6	0.0	–	0.0	12.5	0.0	–	0.8	12.4	2.8	–	0.0	1.3	0.0
Lasthenia californica	–	1.7	5.8	0.0	–	0.3	16.7	0.1	–	0.0	0.0	0.3	–	1.1	0.0	0.0	–	0.0	0.0	0.0

100% coverages (Table 1). From 18 February to 7 June 2004, hydromulch decreased to 20.2% on the GR-100 site, to 9.2% on the GR-50 site and to 4.7% on the GA-50 site (Table 1). By the 7 August 2005 sampling date, there was no hydromulch remaining on the ground (Table 1).

Precipitation and rainfall intensity

Annual average precipitation for the Alpine area is 415 mm. Precipitation was above normal in both the 2004 and 2005 calendar years for both the gabbro and granitic sites (577 and 509 mm on the gabbro sites, and 473 and 431 mm on the granitic sites) (Fig. 3). In 2006, precipitation was below average for both the gabbro and granitic sites (374 and 327 mm) (Fig. 3). For 2004, 2005 and 2006, precipitation was 16% greater on the gabbro as compared with the granitic sites. The wet 2004–05 autumn–winter and drought 2005–06 period are better represented by using the hydrologic year (1 October to 30 September). This interval is often used in Mediterranean climates because hydrological systems are typically at their lowest levels near 1 October. Using this method for the 2004–05 water year, we measured total rainfall of 811 and 694 mm on the gabbro and granitic sites and 368 and 304 mm for 2005–06 (Fig. 3). As shown in Table 2, 61% of the gabbro I10 values were greater than those of the granitics. The 2 April 2004 I10 values preceding the 17 May 2004 cleanout were 29.0 and 16.8 mm h^{-1} on the gabbro and granitic sites. Less than 12 mm of rain was recorded between the 1–4 April rain event and the beginning of the 17–21 October rain event (Fig. 3). The large rain event from 17 to 21 October totalled 158 mm on the gabbro and 135 mm on the granitic. I10 values were 24.1 mm h^{-1} for both 17 and 18 October on the gabbro and 27.1 (17 October) and 22.6 mm h^{-1} (18 October) on the granitic. The highest I10 values were recorded for 23 July 2005: 60.2 mm h^{-1} on the granitic and 39.7 mm h^{-1} on the gabbro (Table 2).

Sediment production

All of the treatments reduced sediment yield during the 37-day period between silt fence installation and the first sediment cleanout of 3 March 2004 (Fig. 4; Table 3). As this was the wettest period in the first 3 months after the fire (precipitation = 164.8 mm gabbro, 136.1 mm granitic), the treatments were likely also effective in reducing erosion during the 2 months before silt-fence installation (Fig. 3). The GR-100 treatment significantly reduced sediment relative to the Control GR, and also showed a significant reduction of sediment when compared with the GR-50 treatment (Fig. 4; Table 4). Sediment yields normalised by total precipitation for the 3 March 2004 cleanout period also showed distinct reductions in sediment on the treated sites (Table 3).

Following the intense 2 April 2004 rain event, both the GR-100 and GR-50 treatments reduced the sediment yield relative to the control, with the GR-100 treatment very close to being statistically significant ($P = 0.072$) (Fig. 4; Table 4). Normalised sediment yields from the GR- and GA-controls were much higher in the second period as compared with the first or third periods (Table 3). Granitic treatments continued to have an effect, but a reduced one as compared with the first sediment cleanout of 3 March 2004. However, there was a significant

Table 2. Rainfall event, rainfall intensity (10 (I10), 30 (I30) and 60 (I60) min) and total rainfall amount compared between gabbro and granitic parent material sites

Values for granitic sites are in parentheses. Table represents rainfall events where I10 (mm h^{-1}) was >20

Rainfall event date	I10 (mm h^{-1})	I30 (mm h^{-1})	I60 (mm h^{-1})	Total amount (mm)
2-Apr-2004	29.0 (16.8)	22.4 (6.6)	16.3 (4.1)	31.2 (12.4)
17-Oct-2004	24.1 (27.1)	11.7 (10.3)	7.2 (5.6)	19.4 (14.6)
18-Oct-2004	24.1 (22.6)	12.9 (12.5)	9.7 (7.2)	139.0 (119.9)
27-Oct-2004	20.5 (19.6)	7.8 (10.7)	4.1 (6.6)	37.1 (36.5)
21-Nov-2004	21.7 (37.6)	12.9 (16.5)	6.6 (7.4)	9.6 (10.5)
28-Dec-2004	21.7 (18.0)	11.4 (8.9)	8.5 (6.4)	79.9 (67.9)
3-Jan-2005	22.9 (18.0)	12.9 (9.4)	7.9 (6.2)	47.9 (34.8)
9-Jan-2005	30.1 (36.1)	18.4 (18.8)	11.2 (9.9)	24.5 (21.4)
28-Jan-2005	32.5 (33.1)	17.6 (16.1)	10.1 (8.0)	19.9 (17.8)
21-Feb-2005	20.5 (19.6)	10.2 (9.4)	7.7 (6.2)	29.0 (27.7)
23-Jul-2005	39.7 (60.2)	16.1 (20.6)	7.9 (8.9)	9.6 (11.2)
1-Jan-2006	29.0 (7.6)	15.2 (5.1)	7.9 (3.8)	30.5 (13.7)
4-Apr-2006	20.0 (15.2)	9.7 (8.6)	7.9 (5.8)	41.7 (34.5)

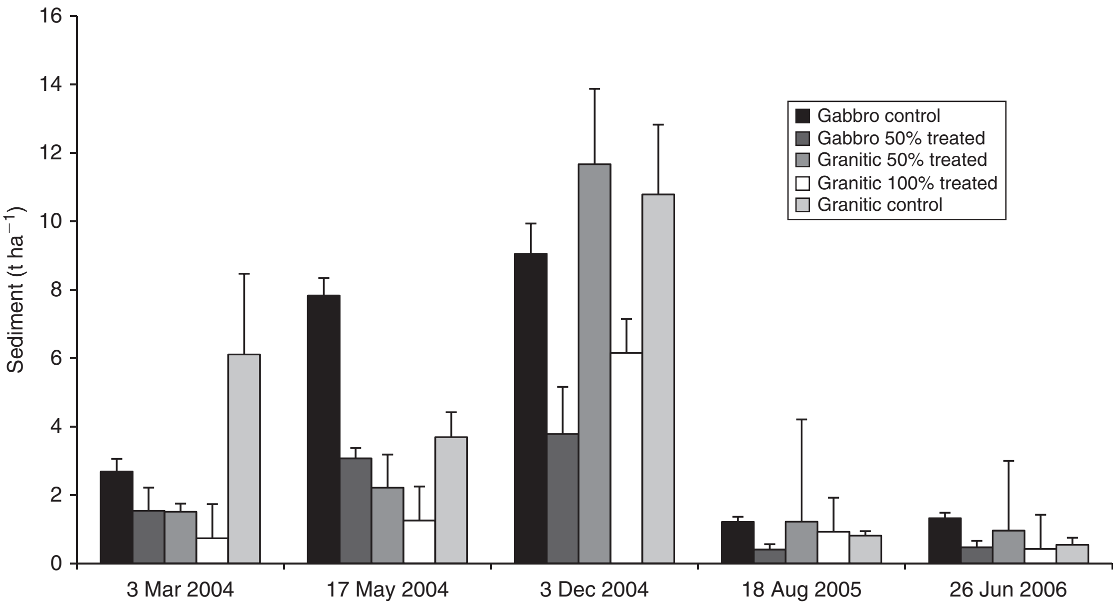

Fig. 4. Sediment production measured on 3 March 2004, 17 May 2004, 3 December 2004, 18 August 2005 and 26 June 2006. Five treatment categories were studied: (1) gabbro control ($n = 13$); (2) gabbro 50% treated ($n = 11$); (3) granitic 50% treated ($n = 10$); (4) granitic 100% treated ($n = 10$); and (5) granitic control ($n = 10$). Error bars for sediment production represent one standard deviation from the mean.

Table 3. Sediment yield normalised by the total precipitation during the period between cleanouts (kg ha^{-1} mm^{-1})

See Table 1 for definitions

Treatment	Cleanout date				
	3-Mar-2004[A]	17-May-2004	3-Dec-2004	18-Aug-2005	26-Jun-2006
Control-GA	16.3	105.9	38.0	2.1	3.9
GA-50	9.3	41.5	15.9	0.7	1.4
GR-50	11.1	51.5	55.8	2.5	3.4
GR-100	5.4	29.1	29.4	1.9	1.5
Control-GR	44.9	86.0	51.6	1.7	1.9

[A]Period measured is from 21 January 2004 (completion of silt fences) to 3 March 2004.

Table 4. Unpaired student *t*-test *P* values of sediment production compared between treatments
See Table 1 for definitions. Probabilities are significant at *, $P < 0.05$

Compared treatments	Sediment production			
	3-Mar-2004	17-May-2004	3-Dec-2004	18-Aug-2005
Control GR *v*. GR-50	0.084	0.230	0.773	0.393
Control GR *v*. GR-100	0.049*	0.072	0.218	0.814
GR-100 *v*. GR-50	0.044*	0.173	0.156	0.571
Control GA *v*. GA-50	0.160	0.001*	0.005*	0.003*
GA-50 *v*. GR-50	0.972	0.368	0.008*	0.066
GA-control *v*. GR-Control	0.184	0.007*	0.449	0.244
	Plant cover			
	18-Feb-2004	7-Jun-2004	5-Jul-2005	27-Jun-2006
Control GR *v*. GR-50	0.084	0.146	0.211	0.275
Control GR *v*. GR-100	0.247	0.614	0.035*	0.124
GR-100 *v*. GR-50	0.490	0.051	0.445	0.006*
Control GA *v*. GA-50	0.348	0.873	0.767	0.026*
GA-50 *v*. GR-50	0.036*	0.068	0.692	0.225
GA-control *v*. GR-Control	0.503	0.808	0.168	0.206

reduction in sediment on the GA-50 sites relative to the Control GA (Fig. 4; Tables 3, 4). In this case, the I10 was 29.0 mm h^{-1} on the gabbro as compared with 16.8 mm h^{-1} on the granitic (Table 2). Additionally, there was a significant difference between the gabbro and granitic control sites (Fig. 4; Table 4).

We measured the highest sediment productions for the 3 December 2004 cleanout (Fig. 4). Because there was no precipitation measured between the 17 May 2004 cleanout and the commencement of the rainfall events beginning 17 October 2004, sediment collected on 3 December 2004 reflected erosion generated primarily by the 2004 October rain events of 17–21 and 27–28 October (Figs 3, 4). Although sediment production was high, there were no significant differences between the granitic treatments and the controls. However, sediment production on the Control-GA was significantly greater than the GA-50 sites (Fig. 4; Table 4). Although both slope and precipitation were greater on the gabbro sites as compared with the granitic sites, sediment production on GR-50 was greater than the GA-50 sites (Figs 3, 4; Table 4). Sediment production declined substantially for all treatments following the 3 December 2004 cleanout (Fig. 4), even though precipitation remained high throughout the 2004–05 winter (Fig. 3). Sediment production was <1.4 t ha^{-1} for the collections dates of 18 August 2005 and 26 June 2006 (Fig. 4). The GA-50 treatment continued to show a significant reduction in sediment relative to the Control-GA (Table 4).

Vegetation cover and individual species recovery

Plant cover ranged from 5.4 to 10.4% for all treatments ~3 months following the fire (Table 1). At this time, there were no significant differences in plant cover observed between the treated sites and the controls, although plant cover on the GA-50 site was significantly greater than plant cover on the GR-50 site (Tables 1, 4). Between 18 February and 7 June 2004, rainfall totalled 210.0 (gabbro) and 150.6 mm (granitic), contributing to an increase in plant cover >18% for all treatments except for GR-50, where measured cover was 13.3% (Fig. 3; Table 1). There were still no significant differences in plant cover observed between the treated sites and the controls (Table 4). Nor were there any significant differences in plant cover between the gabbro and granitic sites, even though precipitation was greater on the gabbro sites (Table 4; Fig. 3). Plant cover increased to 19.7% on the GR-100 as compared with only 13.3% for the GR-50 (Table 1), and was very close to being statistically significant (Table 4). We assumed there was little or no additional plant cover added during the summer 2004 dry period (Fig. 3).

Above-average precipitation totalling 811 and 694 mm for the gabbro and granitic sites was recorded during the 2004–05 hydrologic water year (Fig. 3). Subsequently, plant cover increased dramatically during this time period (Table 1). Plant cover of 74.3% on the GR-100 site was significantly greater than the 61% cover measured on the Control-GR site (Tables 1, 4). There were no other significant differences between the other treated and control sites for the 5 July 2005 sampling (Table 4). Additionally, there were no significant differences between the gabbro and granitic sites, although rainfall continued to be greater on the gabbro sites (Table 4; Fig. 3). Plant cover declined on all treatment and control sites during the below-average 2005–06 hydrologic water year (Table 1; Fig. 3).

Chamise dominated the resprouting shrub cover, exhibiting large increases on the granitic sites following the above-average precipitation of the 2004–05 hydrologic year (Fig. 3; Table 1). Chamise cover increased significantly on the GR-100 hydromulch treatment when compared with the Control-GR ($P = 0.040$). Additionally, at this time, GR-50 chamise cover was significantly greater than chamise measured on GA-50 sites ($P = 0.008$). Chamise cover at the GR-100 site was also significantly higher than the GR-50 site on 27 June 2006 following the drought period (Tables 1, 4). Forb cover also increased dramatically following the above-normal 2004–05 water year, and then exhibited a steep decline following the below-average

2005–06 water year (Table 1; Fig. 3). During this period, morning glory exhibited a significant increase on the GA-50 site as compared with the GR-50 site ($P = 0.001$), but there was no significant growth of morning glory on any of the granitic sites (Table 1). Goldenfields also showed a significant increase on the GA-50 site as compared with the GR-50 site ($P = 0.003$), and again with little or no growth on the granitic sites. Although there were large decreases in both morning glory and goldenfields cover following the below-average 2005–06 hydrologic year (Table 1; Fig. 3), only morning glory cover remained significantly higher than on the GR-50 site ($P = 0.016$). In reversal of the above, catseye exhibited a significant increase on the GR-50 site as compared with the GA-50 ($P = 0.027$) site following the wet 2005–06 water year (Table 1). There was no significant increase in red brome between any of the treatments and the controls (Table 1).

Discussion

Hydromulch

Hydromulch broke down rapidly during the first 6 months following application (Table 1). There was no monitoring of hydromulch at the time of application, so the initial coverage percentage was unknown. Immediately following application, we observed uneven distribution and variation in thickness of the hydromulch on the ground surface. Because the hydromulch mixture is calibrated for an exact delivery height (Caltrans 2003), changes in ground surface topography alter the distance hydromulch travels through the air, thus affecting ground-cover thickness and spatial distribution. Debats *et al.* (2008) noted thickly carpeted areas of hydromulch following hillslope treatment at the Griffith Park Fire, and attributed it to slope variation. Additionally, any change in wind patterns during application can also affect spatial distribution. It is likely that a combination of rain events measuring 121 mm and uneven distribution of hydromulch during application contributed to the reduced cover percentages recorded on 18 February 2004 (Table 1).

The rapid deterioration of hydromulch cover following initial cover measurements (Table 1) was surprising in that: (1) there was less than normal precipitation during the 2003–04 hydrologic year (Fig. 3); (2) storm intensities were fairly low (Table 2); and (3) manufacturer guidelines stated that its structural integrity could sustain multiple storm cycles and that its gradual breakdown would not begin for up to 6 to 12 months following application (Frazier 2003). Because of the rapid breakdown of the hydromulch, we assumed that most of the hydromulch would disappear over the summer of 2004, and therefore provide little protection during the October 2004 storm events (Fig. 3; Table 1). Following the Jesusita Fire in Santa Barbara County, Shank and Steward (2010) noted that it was difficult to see hydromulch on the soil less than 1 year following application.

Hillslope erosion

Hydromulch treatments successfully reduced sediment during a fairly wet period between silt fence installation and the first cleanout (Figs 3, 4); however, I10 values were relatively low, less than $20\ \mathrm{mm\,h^{-1}}$ during this period (Table 2). Because of low plant cover, hydromulch provided most of the cover during this time and was the primary reason for sediment reduction. The significant sediment reduction observed for the GR-100 treatments can be attributed to the fact that hydromulch cover was still 55.8% by 18 February 2004. In comparison, only 26.9% hydromulch remained on the GR-50 sites (Fig. 4; Table 1). The large sediment amounts measured on the Control-GR sites were probably due to the inherent high erosion hazard of the granitic soils (Megahan 1974), and low percentage plant cover (Table 1). Lower sediment production on the Control-GA site as compared with the Control-GR site was likely due to a combination of low intensity of the rainfall events (Table 2) and the 14.4% rock cover of the gabbro terrain as compared with 0.2% rock cover of the granitic soils (Table 1). Poesen *et al.* (1999) noted that surface rock fragments protected the underlying soil more efficiently than a surface free of rocks, especially if soils had been moist for some time. However, percentage rock cover did not appear to play a role in reducing erosion on the gabbro control before the second cleanout (Table 1). In this case, rills were observed forming below the large rock outcrops and boulders on the gabbro sites. In high-intensity rain events, rock outcrops can readily generate infiltration excess overland flow (Litschert and MacDonald 2009) and thus initiate rills.

The high, normalised sediment yields observed on the gabbro and granitic control sites indicated that the high-intensity rainfall event seen in April had a disproportionately large effect on the bare soils (Tables 2, 3). This effect declined as vegetation cover increased (Tables 1, 3). High-intensity, short-duration convective rain events occur infrequently in southern California, where low-intensity, long-duration orographic events are more common (Tubbs 1972). From 2004 to 2006, we observed only four I10 value events $>30\ \mathrm{mm\,h^{-1}}$ and only one event $>40\ \mathrm{mm\,h^{-1}}$ (Table 2). In contrast, frequent summer lightning storm events with I10 values $>70\ \mathrm{mm\,h^{-1}}$ were noted by Spigel and Robichaud (2007) in Montana, and by Baker (1988) in the South-west. The summer monsoon rains common to the South-west seldom move far enough west to affect southern California (Tubbs 1972). Spigel and Robichaud (2007) observed that short-duration, high-intensity storms produced greater sediment loads than rain events of low intensity and long duration, and were the driving factor for first-year post-fire erosion. They measured erosion rates of $81.7\ \mathrm{t\,ha^{-1}}$ following an event with I10 values of $78\ \mathrm{mm\,h^{-1}}$. At I10 values $>70\ \mathrm{mm\,h^{-1}}$, they noted that the influence of site properties such as ground cover, water repellency and steepness of slope were obscured.

We witnessed the highest sediment production almost a year following the wildfire (Fig. 4; Table 3). As there was no rain between the 17 May 2004 cleanout and October 2004, we attributed the majority of the sediment to the two October 2004 storm events (Fig. 3). This raises the question of the usefulness of hydromulch, especially in Mediterranean climates that experience extended dry periods in the spring, summer and autumn. By prescription, hydromulch is supposed to break down within a year, and in our case broke down much more rapidly. Thus in our situation, hydromulch provided no surface protection from erosion processes less than 1 year after the wildfire, and more troubling was the fact that there was no protection at the beginning of what was to be a very wet hydrologic year. In contrast to our results, MacDonald and Robichaud (2008) showed aerial hydromulch reducing sediment yields by 50% 2 years after initial application.

High sediment amounts collected in December 2004 were primarily due to: (1) percentage plant cover remaining low because of the dry summer season (Table 1; Fig. 3); (2) low treatment coverage because of the rapid breakdown of hydromulch (Table 1); (3) large rainfall amounts combined with high intensities (Table 2; Fig. 3); (4) shallow and coarse-textured soils with low water-storage capacity ($\sim$200 mm based on a soil depth of $\sim$80 cm and soil volumetric moisture content of $\sim$0.25 cm cm^{-1}); and (5) subsurface repellency. Normalised sediment yields on the treated granitic sites were very similar to the 17 May 2004 cleanout (Table 3), suggesting that I10 values $>$20 mm h^{-1} occurring on 17 and 18 October (Table 3) were also a factor contributing to sediment production. However, the recorded I10 values were only slightly greater than soil infiltration rates documented for either the gabbro or granitic sites, and thus infiltration excess may have been limited. In addition, we would normally not expect saturation overland flow to occur owing to low average rainfall. Therefore, we believe the unusual 18 October 2004 storm event combining I10 values $>$20 mm h^{-1} and total rainfall of 120 mm (granitic) and 139 mm (gabbro) resulted in near-saturation near the soil surface, which lowered the infiltration rate, allowing for infiltration excess. We also suspect there was subsurface water repellency, which would also impede infiltration, although the BAER team observed no soil water repellency. It is possible that burning destroyed the surface repellency, and significantly increased the persistence of subsurface repellency (Doerr *et al.* 2006). Soils are also known to be highly repellent after long periods of drying, as was the case for our sites (Shakesby *et al.* 2000).

Although precipitation was above normal during the 2004–05 water year and there were five rain events where I10 values exceeded 20 mm h^{-1} (Fig. 3; Table 2), there was very little sediment produced, as observed in the 18 August 2005 cleanout (Fig. 4). Most of the decrease in sediment can be attributed to the rapid increase in plant cover (Table 1). Erosion is effectively controlled at 60% plant cover, even during high-intensity rain events (Robichaud *et al.* 2000). Some of the reduction can also be attributed to the fact that the October storm events removed much of the readily available, unstable and unconsolidated material, thus leaving only modest amounts of easily erodible soil (Figs 3, 4). Wohlgemuth (2006) noted that annual hillslope erosion declined dramatically in subsequent years following the 2003 Williams Fire (in southern California) owing in part to the removal of the easily mobilised sediment from the hillsides that exposed less erodible soil material at the surface.

On our untreated sites, first-year mean post-fire erosion yields of 20.1 t ha^{-1} (Fig. 4) were similar to the 1-year losses of 18.0 t ha^{-1} measured by Robichaud (2005) on a post-fire oak–mixed-conifer site that was also located in southern California. However, our first-year sediment yields were low compared with the 43.1 t ha^{-1} observed by Wohlgemuth (P. M. Wohlgemuth, pers. comm.) on steep slopes $>$55% in southern California. He noted that first-year erosion was highly variable across watersheds owing in part to dry ravel generated during and immediately following the fire. Much greater soil losses of 50–100 t ha^{-1} were reported by Shakesby and Doerr (2006) for a 5-month period following fire in a south-eastern Australian dry sclerophyll forest. Smith and Dragovich (2008) also reported high losses of 94.3 t ha^{-1} in Australian subalpine forests over a 2.2-year period. Menéndez-Duarte *et al.* (2009) reported much lower sediment production of only 6.8 t ha^{-1} in post-fire shrub vegetation of north-west Spain. The above comparisons point out that careful consideration of local climate should be studied before any treatment recommendations are made.

Sediment production was approaching background levels of $<$2 t ha^{-1} year^{-1} less than 2 years following the wildfire. Wohlgemuth (2006) measured prefire background levels of sediment production ranging from 0.9 to 2.4 t ha^{-1} on similar chaparral sites in southern California. In comparison, Pierson *et al.* (2008) reported erosion requiring $>$3 years to return to background levels in a sagebrush-dominated landscape, and MacDonald and Robichaud (2008) reported 3–4 years in a Colorado mixed-conifer forest. In considering the rapid post-fire recovery of chaparral systems and the short time of protection provided by the hydromulch, it might be prudent to replace high-cost hydromulch rehabilitation treatments with less expensive treatments such as straw mulch. Cost of straw mulch can be less than half the cost of aerial hydromulch (Steinke 2010), and has been shown to be as effective or more so than hydromulch (MacDonald and Robichaud 2008). Robichaud *et al.* (2008) noted that straw wattles, another possible hillslope treatment, provided no significant reduction in sediment yields under natural conditions.

Vegetation response

Hydromulch did not appear to affect post-fire plant recovery. Approximately 4 months following the wildfire, plant cover was $<$20% for all treatments, mainly because of the below-average rainfall and shortened growing season (Table 2; Fig. 3). Plant cover increased to $>$60% at all sites following the above-average 2004–05 hydrologic year (Table 1). Manufacturer product specifications claim that mixtures are porous enough, even at 100% coverage, not to inhibit plant growth (Caltrans 2003). Hydromulch appeared to benefit plant growth on the GR-100 sites (Table 1) by increasing soil moisture retention (decreased soil evaporation) and improving infiltration by allowing greater water retention time (Caltrans 2003). On the 50%-treated gabbro sites, increased plant cover was also attributed to the higher clay contents of the gabbro soils, which provided more water-holding capacity and increased cation-exchange capacity (Morris 2001). Kwok *et al.* (2008) noted that the application of aerial hydromulch had no significant detrimental effects on post-fire vegetation recovery following the 2007 Griffith Park Fire. However, Debats *et al.* (2008) noted higher plant densities in non-hydromulch areas as compared with hydromulch areas for the same fire, suggesting that hydromulch was acting as a physical barrier impeding vegetation recovery.

Chamise basal resprouting was observed as soon as 2 weeks after the fire. In most cases, belowground lignotubers and roots were not killed by the fire and allowed rapid recovery by providing nutrients and water to the resprouting plant (Hubbert 2006). Because of their ability to access water stored deep in the soil, resprouting shrubs continued to increase throughout the post-fire period (Table 1). The intact roots also provided protection to the hillslopes from soil slippage and shallow landslides (Sampson 1944). On the granitic soils, chamise showed a much stronger growth in response to the hydromulch as compared with chamise on the gabbro treated sites (Table 1). On the gabbro treated sites, hydromulch may have increased the surface soil water-holding capacity, favouring the rapid growth of morning glory and goldenfields, which may, in turn, have out-competed the chamise for available nutrients (Table 1) (D'Antonio 2000).

Morning glory and goldenfields cover showed a large increase on the gabbro sites following the wet 2004–05 hydrologic year (Table 1; Fig. 3). As a matter of interest, there was very little growth of the two species on the granitic sites, suggesting a nutrient relationship inherent to mineralogical differences between gabbro and granitic soils (Table 1). In contrast, catseye was more abundant on the treated granitic soils, with its growth strongly influenced by the hydromulch. Most of the morning glory and goldenfields died during the dry 2005–06 water year (Table 1; Fig. 3), and was falling over and forming mats on the ground. The dead vines of morning glory were thick and difficult to walk through. Increased amounts of dead litter (Table 1) as a result of accelerated growth of natives and invasive annual grasses when combined with drought are a major concern to ecologists in the area (Halsey 2008). Dead plant material and litter can carry fires through the chaparral. Reducing the time intervals between fires can result in type conversion of the chaparral community as resprouting species do not have time to recover (Halsey 2008). The invasive grass red brome did not appear to be influenced by the hydromulch, but increased following the wet 2004–05 winter, and then declined rapidly during the 2005–06 drought (Table 1).

Conclusions

Hydromulch was effective in reducing erosion following the wildfire; however, its benefits appeared to be limited to the first 2–4 months following fire, raising doubts as to its overall cost-effectiveness. On the granitic sites, the 100% treatment was more effective in reducing sediment than the 50% treatment. In regard to cost savings, it might be more economical to use the 50% treatment and sacrifice some sediment control. It might also be beneficial to consider less expensive treatments such as straw mulch. The breakdown of the hydromulch was more rapid than indicated by the manufacturer's specifications. Because of its rapid breakdown, the hydromulch provided little hillslope protection during the above-average October 2004 storm events. Both rainfall amount and I10 values $>20\ \mathrm{mm\,h^{-1}}$ played a role in the magnitude of sediment production observed during the storm events of October 2004.

Hydromulch coverage did not have a negative effect on post-fire plant recovery for either the gabbro or granitic sites. Vegetation cover averaged >60% at all sites by 7 August 2005, less than 2 years following the fire. Chamise showed a strong response in growth to the hydromulch on the granitic sites as compared with the untreated sites. Both morning glory and goldenfields increased on the gabbro sites treated with hydromulch. In contrast, catseye exhibited the greatest increase on the treated granitic sites. Invasive grasses did not appear to be influenced by the hydromulch. The accelerated growth of the herbaceous species suggested that hydromulch provided additional moisture to the soil, allowing additional water and nutrient uptake later into the growing season. Die-off of this new growth and subsequent increase in litter and dead fuels could promote wildfires and shorten fire return intervals, resulting in possible negative effects to the chaparral community.

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