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Initial impacts of a wildfire on hydrology and suspended sediment and nutrient export in California chaparral watersheds

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Abstract:

Stream and rainfall gauging and runoff sampling were used to determine changes in hydrology and export of nutrients and suspended sediment from a June 2004 wildfire that burned 3010 ha in chaparral coastal watersheds of the Santa Ynez Mountains, California. Precipitation during water year 2005 exceeded average precipitation by 200–260%. Burned watersheds had order of magnitude higher peak discharge compared with unburned watersheds but similar annual runoff. Suspended sediment export of 181 mt ha^{-1} from a burned watershed was approximately ten times greater than from unburned watersheds. Ammonium export from burned watersheds largely occurred during the first three storms and was 32 times greater than from unburned watersheds. Nitrate, dissolved organic nitrogen, and phosphate export from burned watersheds increased by 5.5, 2.8, and 2.2 times, respectively, compared with unburned chaparral watersheds. Storm runoff and peak discharge increase in burned compared with unburned sites were greatest during early season storms when enhanced runoff occurred. As the winter progressed, closely spaced storms and above average precipitation reduced the fire-related impacts that resulted in significant increases in annual post-fire runoff and export in other studies in southern California chaparral. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS nutrient export; sediment export; wildfire; chaparral; runoff

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INTRODUCTION

Climatic conditions and changes to land cover influence the quantity and chemical characteristics of runoff delivered by rivers to coastal waters, and recent analyses have indicated that small rivers in mountainous catchments can make large contributions (Smith *et al*., 2003). Coastal California represents a prime example of a region with many small rivers draining mountainous catchments with varied and changing land cover and with large seasonal and inter-annual variations in runoff. In particular, numerous streams originate in the mountains fringing the northern coast of the Santa Barbara Channel, California, and transport nutrients and sediments into coastal estuaries and the near-shore oceanic environment (Goodridge and Melack, 2012). Furthermore, fires are common in coastal watersheds and result in episodic alterations in hydrology and export of solutes and suspended sediment. Although there have been numerous studies of the effects of fire on sediment erosion, transport, and deposition (Shakesby and Doerr, 2006, Shakesby, 2011), few watershed-scale studies have determined nutrient export to coastal waters in California or other regions with similar climate and topography (Verkaik *et al*., 2012).

Fires alter hydrologic response by reducing infiltration (Debano, 1981; Wells, 1987; Debano *et al*., 1998; Gabet, 2003), evapotranspiration, and interception (Tiedemann *et al*., 1979; Wells *et al*., 1979), and the magnitude of responses depend on the severity of the fire, type and amount of vegetation burned, topography, and geologic setting (Debano and Conrad, 1976; Wells *et al*., 1979; Earles *et al*., 2004). The fire-induced change in hydrologic response contributes to increased soil erosion (Wells, 1987), sediment mobilization and transport (Rice, 1974), and nutrient export (Debano *et al*., 1998).

In southern California chaparral ecosystems, watershed-scale studies focusing on fire's impact on nutrient fluxes have been limited to watersheds experiencing high atmospheric nitrogen deposition within the San Dimas Experimental Forest (SDEF) (Riggan *et al*., 1994; Meixner *et al*., 2006). Measurements made after prescribed burns in the SDEF indicated that ammonium concentrations peaked in the ash-laden flows during the first few storms of the season with ammonium concentrations dropping 1 to 2 orders of magnitude in subsequent storms (Riggan *et al*., 1994). Riggan *et al*. (1994) found a 40 times increase in annual post-fire nitrate flux in the first year, and Meixner *et al*. (2006) reported that stream nitrate concentrations and export remained high for 7–10 years after fire when compared with unburned control catchments. Little has been reported on post-fire phosphorous concentrations in runoff from southern California chaparral watersheds. Debano and Conrad (1978) found that the phosphorous contained in chaparral vegetation and litter was deposited on the soil surface as ash and subject to loss from surface erosion. Increased concentrations would be expected in early season storms as thin debris flows transport ash and soil into streams.

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Although several studies have demonstrated that watershed responses increase in the first year after a fire, the magnitude of the responses will depend on the frequency and intensity of rainfall as well as the characteristics of the fire and watershed (Scott *et al*., 1998; Debano, 2000). Only a small subset of the many combinations of these conditions has been examined in watersheds dominated by chaparral and subjected to large variability in rainfall and runoff. The occurrence of a wildfire in the coastal mountains west of Santa Barbara, California, in June 2004, followed by a rainy season with precipitation totals 200–260% above the 35-year average provided an opportunity to examine responses to fire under conditions of enhanced runoff. The area is subject to low levels of atmospheric nitrogen deposition; hence, our study will determine if increases in annual post-fire export are of a comparable magnitude to those found in southern California chaparral watersheds subject to high levels of atmospheric nitrogen deposition. Because stream discharges and solute concentrations in both burned and unburned neighbouring watersheds were being measured as part of an on-going investigation, changes in hydrologic response and nutrient (nitrate, ammonium, dissolved organic nitrogen, and phosphate) and suspended sediment export from burned coastal California chaparral watersheds could be determined in comparison with similar unburned watersheds. Hence, we examine the question: How much is the export of nutrients and suspended sediments enhanced after wildfire in mountainous watersheds with natural chaparral vegetation in years with high rainfall?

STUDY AREA

The study area is located in southern California on the coast of the Santa Barbara Channel and includes three watersheds draining the Santa Ynez Mountains (SYM) of the Transverse Range (Figure 1). The Arroyo Hondo (1085 ha; ridgeline 856 m asl) and San Onofre (526 ha; ridgeline 792 m asl) watersheds drain the south-facing slopes of the SYM and reach from the coast to the ridgeline. The Gaviota watershed (5216 ha) drains the south-facing slopes of the SYM and a significant portion of the watershed also drains an area (4550 ha) located north of the SYM ridgeline. Arroyo Hondo and San Onofre are primarily native chaparral and oak woodlands with only a small amount of development (6 ha of abandoned avocado and citrus trees) at the bottom of Arroyo Hondo. Both creeks have concrete culverts running underneath a highway before discharging into the Santa Barbara Channel. The southern 1230 ha of the Gaviota watershed is largely native chaparral and oak woodlands and the upper portion contains coastal sage, open grasslands, oak, and chaparral. The area is characterized by Miocene and Eocene marine sandstone, siltstone, and mudstone sedimentary bedrock (Dibblee, 1988a,1988b) and is capable of producing high sediment export (Inman and Jenkins, 1999; Warrick and Mertes, 2009).

The climate of southern California is considered Mediterranean. Beighley *et al*. (2005) reported that 80% of annual precipitation generally falls between the months of December and March. Winter storms along the Santa Barbara Channel often have significant orographic enhancement when encountering the SYM. Precipitation during water year (WY) 2005, from 1 October 2004 to 30 September 2005, exceeded average precipitation amounts for the study area. A precipitation gauge 2 km east of Gaviota watershed recorded 148 cm (200% of average with an average occurrence interval of approximately 40 years), and a gauge 0.5 km east of Arroyo Hondo watershed recorded 144 cm (260% of average with an average occurrence interval of approximately 200 years) based on 35 years of record (Santa Barbara County Public

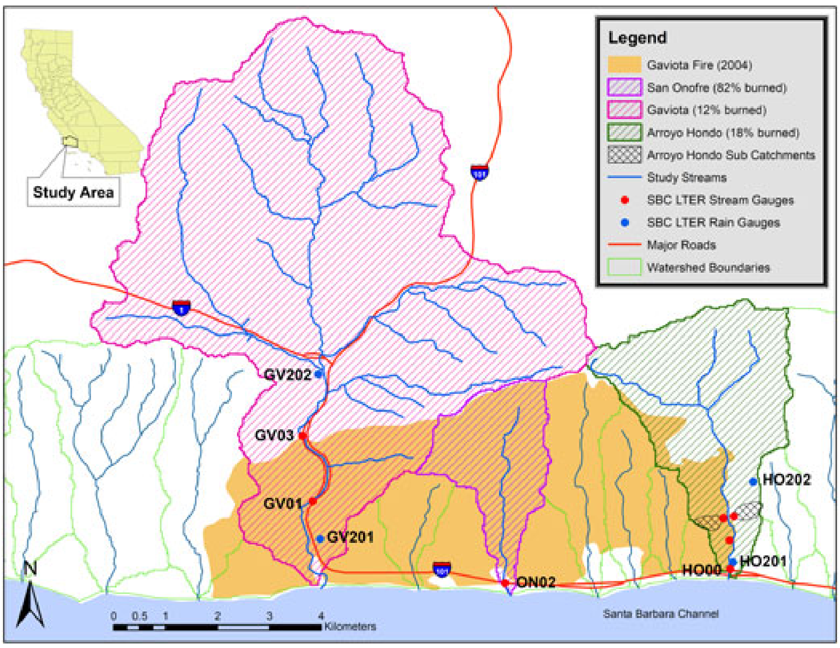

Figure 1. Location of watersheds and gauges and extent of Gaviota fire. Gaviota (GV), San Onofre (ON), and Arroyo Hondo (HO)

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Works Department, 2011). Most of the precipitation in WY2005 occurred in periods from 26 December 2004 to 11 January 2005, and from 16 to 23 February 2005.

Prior to 2004, the last major fire in the study area was the Refugio fire of 1955 that burned 1223 ha in the eastern portion of the Gaviota watershed, most of the San Onofre watershed and the entire Arroyo Hondo watershed. The most recent fire, and the focus of this research, was the Gaviota fire that occurred from 5 to 12 June 2004. The fire consumed 3010 ha on the south-facing slopes of the SYM and a small portion north of the SYM ridge in the Gaviota watershed (Figure 1). The burn severities for the Gaviota fire's footprint were 56% low, 27% moderate, 13% high, and 4% unburned. Burn severity is based on pre-fire vegetation types and visual inspection of post-fire condition of remaining fuels, and does not necessarily correspond to formation of hydrophobic soils.

METHODS

Sampling and gauging locations (Figure 1) and periods

Sampling and stream gauging at the outlet of the Arroyo Hondo watershed and approximately 2 km upstream of the outlet of the Gaviota watershed were conducted in WY2002 through WY2005. During the Gaviota fire, 18% and 7% of the gauged contributing area in Arroyo Hondo and Gaviota, respectively, were impacted by the fire. Additional gauging and sampling sites were added in WY2005: one located just upstream of the burned area in the Gaviota watershed and a second located 200 m upstream of the outlet of the San Onofre watershed, of which 82% was burned. Two subcatchments located within the Arroyo Hondo watershed were chosen to make a comparison between burned and unburned areas. The subcatchments had approximately the same area (11.9 ha and 13.7 ha), were situated in the same bed of the east–west trending Sespe Formation, located on opposite sides of the main drainage channel, and flowed only during and shortly after rainfall.

Because WY2005 precipitation and discharge exceeded pre-fire conditions from WY2002 to WY2004, unburned Rattlesnake Canyon watershed, located 45 km east and with data from WY2002 through WY2005 was included for comparison. Two additional watersheds with different land uses are included in the discussion: Mission, with 55% urban, and Bell Canyon, with 24% agriculture, and located 40 km and 22 km, respectively, east of the main study area (Goodridge and Melack, 2012). Watershed basin characteristics are listed in Table I.

Stream and rain gauging

Pressure transducers (Solinst model 3001 Levelogger) were installed in the streams to record stage at 5 min intervals. The pressure data were converted to stage by subtracting the corresponding local atmospheric pressure (a barometric pressure gauge was located adjacent to the stream gauge in Arroyo Hondo) and by making adjustments based on manually measured stage, taken from a permanent, established datum adjacent to each pressure transducer. The accuracy of the compensated and adjusted data was generally $\pm$ 1.5 cm.

Stage to discharge rating curves were created by an indirect method using the US Army Corps of Engineers' Hydrologic Engineering Center River Analysis System programme (HEC-RAS) and calibrated using periodic manual discharge measurements collected with an electromagnetic current metre. Stream cross-sections and slopes were surveyed and entered into the HEC-RAS programme along with stream channel roughness (Manning's n) to calculate stream surface height and cross-sectional averaged velocity for a given discharge at each cross-section using the step-backwater method (USACE, 2001). Sensitivity analysis of HEC-RAS generated rating curves indicated an uncertainty of 5–10% for discharges greater than $3\,m^3\,s^{-1}$ and 10–50% for discharges less than $3\,m^3\,s^{-1}$. Discharge data in San Onofre Creek were lost because of transducer malfunction from 1 October to 3 December 2004 and were estimated from linear regression from measurements in Arroyo Hondo and Gaviota creeks. Gauged discharges from Arroyo Hondo and Gaviota creeks were regressed against gauged discharge in San Onofre Creek during the period 3–31 December 2004, when similar storms occurred ($R^2 = 0.64$). San Onofre Creek discharges estimated through linear regression were further adjusted based on manual stage measurements and high water marks collected during the period of missing data.

Precipitation was measured using tipping bucket rain gauges (Qualimetrics model 6011B with resolution of 0.1 mm and an accuracy of 0.5% at a rainfall rate of $1.3\,cm\,hr^{-1}$; Sutron model 5600-0425-2 with resolution

Table I. Characteristics of watersheds

Watershed	Area (ha)	Average elevation (m)	Average slope	Relief (m)	Land use percentage					
					Agric. (%)	Other (%)	Forest (%)	Shrub (%)	Range (%)	Urban (%)
Gaviota	5216	288	29.6	851	0	1	21	36	41	0
San Onofre	526	420	40.3	792	0	1	14	82	3	0
Arroyo Hondo	1085	443	39.7	856	0	1	15	81	4	0
Rattlesnake	574	625	39.0	874	0	0	14	85	0	1
Mission Creek	2997	389	26.5	1208	2	1	8	34	0	55
Bell Canyon	1466	285	31.0	934	24	1	11	57	5	3

of 0.2 mm and an accuracy of 2% at a rainfall rate of 5 cm hr^{-1}). The height of the gauge orifices was 1–1.3 m above ground surface, and gauges were calibrated preceding the onset of the rainy season. Rain gauge data were also used from two Santa Barbara County rain gauges located at Tajiguas Landfill (0.5 km east of the Arroyo Hondo watershed) and Nojoqui Falls Park (2 km east of Gaviota watershed); these were tipping bucket gauges with a resolution of 0.25 mm. Further details about stream and rain gauging are provided in Coombs (2006)

Stream and precipitation sampling

Stream water samples were collected manually (grab) or by auto-samplers (ISCO 6712C) with a suction hose in the channel. Water samples were taken every 2 weeks from May through October, once a week from November through April, and every 1–4 h during rainfall. The frequency of sampling during rainfall was typically hourly throughout the rising limb of the hydrograph and increased to several hours as flow subsided to pre-storm levels. All samples were collected in high-density polyethylene (HDPE) bottles, which had been rinsed with deionized water. During low flow, an aliquot was filtered through a Gelman A/E glass fibre filter (porosity 1 μm) in the field, and during stormflow, filtering was carried out in the laboratory usually within a day or two of delivery. Samples were placed in a cooler and transported within 24 h to the laboratory for storage at 4 °C.

Rain samples for chemical analyses were collected 25 km east of the main study area (34.4°N, 120.07°W) with a 20 cm diameter polypropylene funnel inserted into a HDPE 2 l bottle. Both funnel and bottle were rinsed with deionized water before deployment and placed outside prior to a forecasted storm event. Precipitation was measured using a gauge located adjacent to sample collector.

Sample processing and analysis

Dissolved NH_4, NO_3, and PO_4 were assayed on a Latchet Flow Injection Analyzer. Total dissolved nitrogen (TDN) was determined after persulfate oxidation (Valderrama, 1980) followed by measurement of NO_3. Nitrate was measured by the Griess–Ilosvay reaction after Cd reduction with a detection limit of 0.5 μM, sensitivity ± 0.2 μM and accuracy ± 5%. Ammonium was measured after conversion to ammonia with a detection limit of 0.5 μM, sensitivity 0.2 μM, and accuracy ± 5%. Soluble reactive phosphorus was measured after reaction with ammonium molybdate and antimony potassium tartrate and reduction by ascorbic acid; detection limit was 0.3 μM, sensitivity was ± 0.2 μM, and accuracy was ± 10%. Dissolved organic nitrogen (DON) concentration was determined by subtracting ammonium and nitrate concentrations from TDN concentrations. Coombs (2006) provides further information about analytical procedures and sample storage evaluations.

Total suspended solids were determined on samples with low amounts of suspended sediment by filtering a known volume of well mixed sample onto a tared 47 mm Gelman A/E filter. After drying at 105 °C for 2 h, the weight of the filter plus residue was obtained on a Mettler Toledo AB104-S analytical balance (Method B; ASTM-D 3977-97, 1997). Suspended sediment concentrations (SSC) were measured on samples with large amounts of sediment in a tared 250 ml polypropylene centrifuge bottle, if the sample remained well mixed after shaking, or in a 500 ml polypropylene centrifuge bottle, if rapid settling of sediment was observed. The samples were then weighed. After allowing the sample to settle and decanting the clear water, the bottles were first heated at a temperature slightly below boiling until all visible water was gone and then at 105 °C for 2 h. The dried bottles were reweighed and SSC calculated in accordance with ASTM D 3977-97 (Method A).

Calculations

A storm was defined as a precipitation event (typically exceeding 1 cm of rain) resulting in a measured increase in stream discharge. Runoff depth (m) was determined by taking the total volume of storm discharge (m^3) and dividing by the watershed's contributing area (m^2). Instantaneous runoff ($m\,s^{-1}$) was determined by dividing discharge ($m^3\,s^{-1}$) by contributing area (m^2). Runoff coefficients were calculated by dividing an event's runoff depth by the catchment's weighted precipitation during the event. Weighted precipitation was determined by multiplying gauged precipitation by a factor determined by spatial analysis from the intersection of PRISM contours (Beighley *et al.*, 2003) with a watershed's contributing area. Peak instantaneous discharge ($m\,s^{-1}$) was determined by dividing a storm's maximum 5-min discharge rate ($m^3\,s^{-1}$) by the watershed's contributing area (m^2).

Export refers to either the storm or annual sum of moles of nutrients or tonnes of sediment per hectare (ha). Stream discharge data measured in 5-min intervals were averaged to 15-min intervals. Nutrient or suspended sediment concentrations were linearly interpolated to determine concentrations between sampling times, and gap filling procedures were required 5 to 8% of the time in WY2005 (Coombs, 2006).

RESULTS

Hydrologic responses

The Gaviota fire occurred in June 2004, following a winter season with 73% of average rainfall that resulted in low flows and the lower portions of the stream channel becoming dry in San Onofre, Arroyo Hondo, and Rattlesnake watersheds. Before the onset of the first storm of WY2005 on 16 October 2004, the last precipitation event with >1 cm of rain occurred 7 months earlier. WY2005 was characterized by several early season storms (October and November 2004) when the soils throughout the watersheds were dry, and a series of major winter storms (December 2004 to March 2005) when watershed soils approached saturation. These early season storms and major winter storms (defined as those with >1 cm of runoff) represent 72 to 85% of the

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WY2005 runoff from the study sites. Twelve additional rainfall events occurred, but each had <1 cm of runoff (<1% per storm of total WY2005 runoff); these are included in WY2005 totals.

Peak instantaneous discharges in San Onofre Creek tended to be an order of magnitude greater than those in Rattlesnake Creek and were higher than peak discharges in Arroyo Hondo Creek until late March. In the Arroyo Hondo burned and unburned subcatchments, peak instantaneous discharges were consistently greater in the burned subcatchment (Figure 2). Peak instantaneous discharges were up to two orders of magnitude greater and averaged 35 times greater for the burned catchment. Time from precipitation event to peak discharge was typically 10–20 min shorter for the burned subcatchment with the longest response time difference occurring after prolonged dry periods and the shortest differences occurring during extended rainy periods.

The runoff coefficient for an early October 2004 storm of 7–13 cm in the San Onofre watershed was greater (0.16) than that for Rattlesnake watershed (0.03) or the partially burned watersheds of Gaviota (0.01) and Arroyo Hondo (0.05). Following the 19–20 October and 26–27 October 2004 storms, the runoff coefficient in San Onofre watershed was about 4 to 5 times greater than in Rattlesnake watershed and 2 to 3 times greater than in Arroyo Hondo (Figure 3) watershed. This trend changed during the December 2004 to January 2005 storms, with San Onofre runoff coefficient only 16% greater than Rattlesnake and approximately equal to Arroyo Hondo. Runoff coefficients in Gaviota watershed remained lower than those at the other sites.

Sediment fluxes

Sediment movement by dry ravel occurred in the burned catchments immediately following the fire, and cones of sediment were observed forming at the base of hillslopes and in tributary stream channels in August 2004. In late October 2004, the San Onofre watershed experienced a debris flow that carried trees (up 30 cm diameter), brush, and

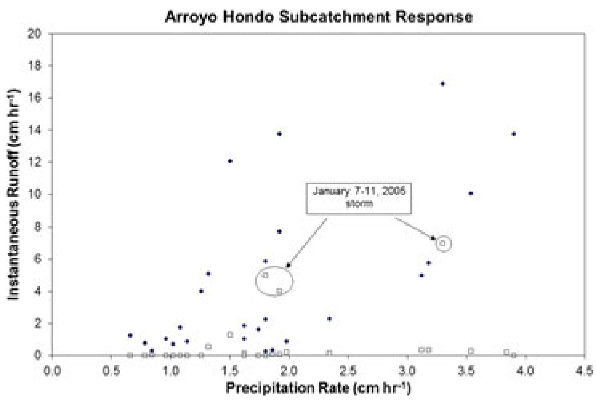

Figure 2. Arroyo Hondo subcatchment [HO21 (solid symbol) and HO31 (open symbol)] responses to specific precipitation events. Instantaneous runoff is significantly greater in the burned than unburned subcatchment for a given precipitation rate. An outlier for HO21 is not shown for instantaneous runoff of 46.2 cm hr^{-1} and precipitation rate of 3.8 cm hr^{-1}

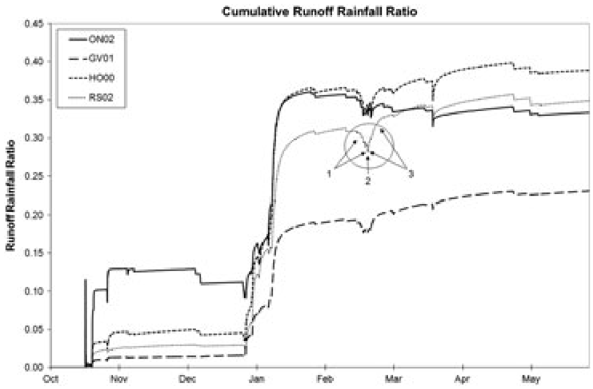

Figure 3. The cumulative runoff rainfall ratio calculated by dividing cumulative discharge by cumulative weighted precipitation on an hourly basis for Gaviota (GV01), San Onofre (ON02), Arroyo Hondo (HO00), and Rattlesnake (RS02) watersheds. The typical late season pattern (circled) shows a decrease in the ratio at the onset of a precipitation event (1), reaching a minimum as runoff peaks (2), and an increase as precipitation ends and the hydrograph recedes

large boulders downstream. Caltrans removed an estimated 800 tonnes of trees and brush from the channel (S. Sinet, personal communication) at the culvert under the highway. Samples collected at the burned sites during the October 2004 storms had visibly high suspended sediment loads, a dark grey colour, and a strong odour of burned materials. For a given storm, peak concentrations of suspended sediments generally coincided with peaks in the hydrograph and rapidly decreased as the hydrograph receded, but different patterns were observed among the San Onofre, Gaviota, and Arroyo Hondo watersheds.

Early season storms (October to mid-December) at Gaviota had very high suspended sediment concentrations (from 40 to 186 g l^{-1}) at relatively low discharge rates (<5 $m^3 s^{-1}$) (Figure 4(a)). During this period, numerous debris flows occurred in the burned portion and rill formation on the hillsides was widespread. The stream channel, usually dominated by gravel to boulder-sized bed material, was filled with up to 1 m of sand and silt. Concentrations remained high (from 40 to 80 g l^{-1}) and discharge reached 40 $m^3 s^{-1}$ in late December, and much of the sand and silt deposited earlier was moved downstream. For the remaining storms of the season, suspended sediment concentrations remained below 40 g l^{-1} and were within the concentration range of pre-fire samples collected in WY2003. The suspended sediment concentrations were much greater at the lower Gaviota sampling site than the one above the burned area before late December, but afterwards both sites were similar.

In the San Onofre watershed, early season storms had high concentrations (from 50 to 250 g l^{-1}) at discharges below 5 $m^3 s^{-1}$ and remained high (up to 250 g l^{-1}) throughout the season (Figure 4(b)). Following each major storm, large amounts of bed load were observed to have moved, with up to 1-m boulders being transported downstream. The short-lived, but intense storm on 22 March 2005, deposited large quantities of cobble to sand sized sediment, with approximately 0.3 m being deposited inside the highway culvert.

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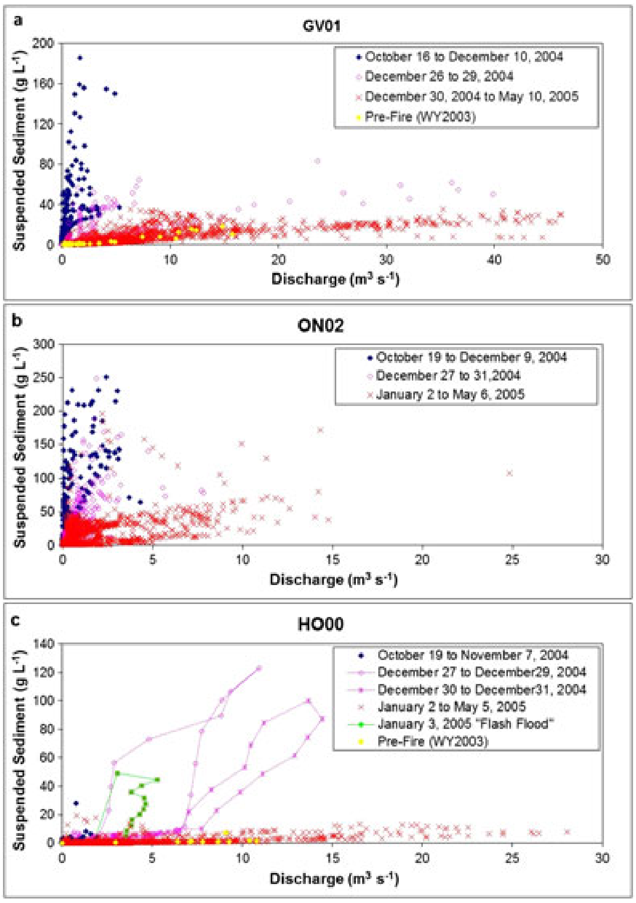

Figure 4. Discharge-suspended sediment concentration trends over the course of pre-fire WY2003 and post-fire WY2005 for Gaviota (GV01), San Onofre (ON02), and Arroyo Hondo (HO00) watersheds

In Arroyo Hondo watershed, suspended sediment concentrations were within the range of pre-fire concentrations ($<10\,g\,l^{-1}$) during the early season storms, except for the first flush sample collected on 19 October 2004 (Figure 4 (c)). As shown in the clockwise hysteresis in Figure 4(c), the two major late December storms had order of magnitude increases in suspended sediment concentrations in comparison with pre-fire WY2003 measurements. A third pulse of high suspended sediment concentrations occurred during an intense rainfall on 3 January 2005. Subsequently, suspended sediment concentrations remained below $15\,g\,l^{-1}$ and within the range of WY2003 measurements, except for the first flush on 19 February 2005, which coincided with the highest peak discharge measured in the nearby San Onofre Creek.

The suspended sediment export in metric tonnes (mt) from Gaviota, San Onofre, and Arroyo Hondo watersheds for WY2005 was 38, 181, and $26\,mt\,ha^{-1}$, respectively. Nearly half the annual suspended sediment export from the Gaviota watershed occurred from 7–11 January 2005; this storm accounted for about 30% of the annual export from San Onofre and Arroyo Hondo watersheds.

Nutrient concentrations and fluxes

Volume-weighted mean (VWM) concentrations of nitrate in San Onofre Creek ranged from 89 to 217 μM for the first three storms of the season, peaked during late December 2004 storms with individual values as high as 749 μM, but with marked declines during large early January storms (Figure 5), and progressively decreased over the succession of later storms. For the storms from late December 2004 through March 2005, nitrate comprised over 85% of total nitrogen export from San Onofre watershed. VWM nitrate concentrations in Gaviota and Arroyo Hondo creeks were generally between 100 and 200 μM, whereas those in Rattlesnake Creek were usually less that 100 μM during the late December and early January storms (Figure 5). For WY2005 nitrate fluxes of $1620\,mol\,ha^{-1}$ (San Onofre), $235\,mol\,ha^{-1}$ (Gaviota), $773\,mol\,ha^{-1}$ (Arroyo Hondo), and $293\,mol\,ha^{-1}$ (Rattlesnake) were recorded. Cumulative export during the course of the WY reflected interplay of enhanced concentrations associated with the fires and the discharges per storm (Figure 6).

Ammonium export during the first three storms of WY2005 accounted for 32 and 38% of the total dissolved nitrogen export from San Onofre and Gaviota watersheds, respectively. During these storms, maximum ammonium concentrations of 523 and 350 μM occurred in Gaviota and San Onofre creeks, respectively, and coincided with peaks in discharge. As the year progressed, concentrations decreased one to two orders of magnitude, and the contribution of ammonium to total dissolved nitrogen diminished. In undisturbed watersheds, ammonium export in WY2003, 2004 and 2005, as a fraction of total dissolved nitrogen, was below 3% for individual large storm totals and 1% for annual totals. In undisturbed watersheds, maximum concentrations were approximately 10 μM. For WY2005 ammonium fluxes of $73\,mol\,ha^{-1}$ (San Onofre), $7.5\,mol\,ha^{-1}$ (Gaviota), $7.4\,mol\,ha^{-1}$ (Arroyo Hondo), and $2.3\,mol\,ha^{-1}$ (Rattlesnake) were recorded. Cumulative export shows the dominance of the early season storms with high ammonium concentrations in San Onofre Creek (Figure 6).

DON export comprised 43 and 52% of the total dissolved nitrogen export during the three early season storms in the San Onofre and Gaviota watersheds, respectively. In these storms, VWM concentrations at the burn impacted sites ranged from 84 to 366 μM in San Onofre Creek and 125 to 198 μM in Gaviota Creek. For WY2005 DON fluxes of $226\,mol\,ha^{-1}$ (San Onofre),

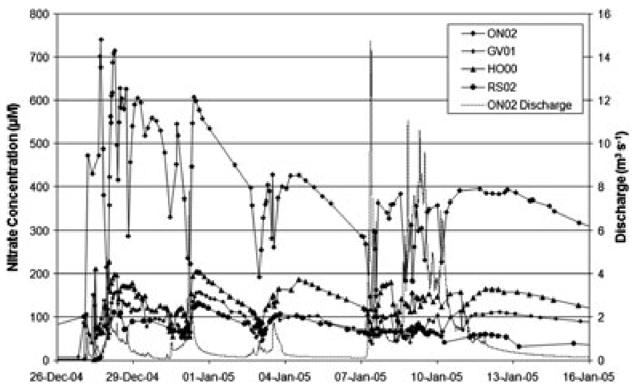

Figure 5. Nitrate concentrations during the 27 December 2004 to 11 January 2005 series of major storms for San Onofre (ON02), Gaviota (GV01), Arroyo Hondo (HO00), and Rattlesnake (RS02) watersheds

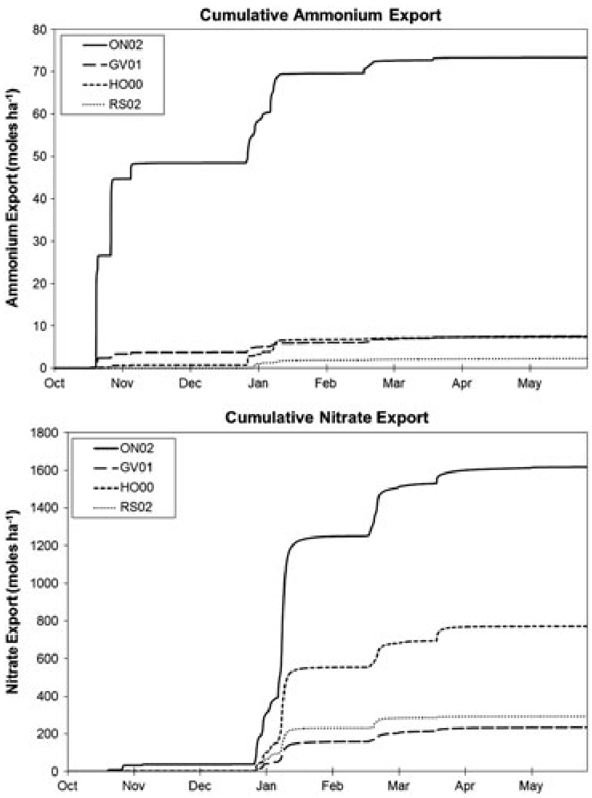

Figure 6. Cumulative ammonium export (upper panel) and cumulative nitrate export (lower panel) for San Onofre (ON02), Gaviota (GV01), Arroyo Hondo (HO00), and Rattlesnake (RS02) watersheds

104 mol ha^{-1} (Gaviota), 151 mol ha^{-1} (Arroyo Hondo), and 81 mol ha^{-1} (Rattlesnake) were recorded (Figure 7).

Phosphate concentrations at burned and unburned sites spiked upwards with increases in discharge and returned to near baseflow levels as discharge receded. VWM concentrations peaked at 10 μM in San Onofre Creek and at 7 μM in Arroyo Hondo Creek during the early season storms, but peaked at 27 μM in Gaviota Creek in early January. For WY2005 phosphate fluxes of 24 mol ha^{-1} (San Onofre), 73 mol ha^{-1} (Gaviota), 24 mol ha^{-1} (Arroyo Hondo), and 11 mol ha^{-1} (Rattlesnake) were recorded (Figure 8).

DON comprised 51% of TDN wet deposition of between 246 and 287 mol ha^{-1}, and ammonium and

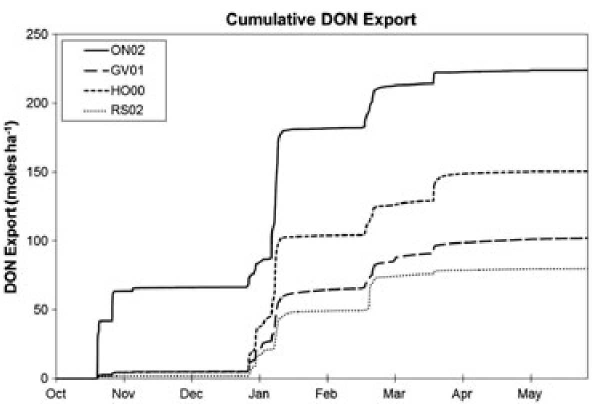

Figure 7. Cumulative dissolved organic nitrogen export for San Onofre (ON02), Gaviota (GV01), Arroyo Hondo (HO00), and Rattlesnake (RS02) watersheds

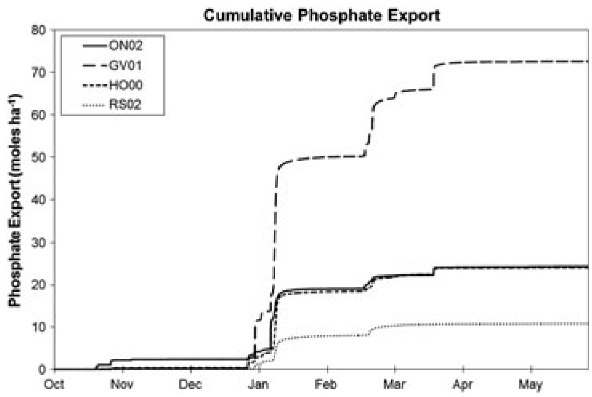

Figure 8. Cumulative phosphate export for San Onofre (ON02), Gaviota (GV01), Arroyo Hondo (HO00), and Rattlesnake (RS02) watersheds

nitrate comprised the remaining 19 and 30%, respectively. Phosphate wet deposition remained below 1.2 mol ha^{-1}. Annual export was an order of magnitude greater than wet deposition for all sites.

DISCUSSION

Hydrologic responses

The reduction in evapotranspiration and infiltration capacity associated with wildfires typically results in greater and flashier discharge at burn impacted sites in comparison with unburned sites (Debano *et al*., 1998). Hubbert *et al*. (2006) tracked the changes in water repellency at the soil surface in a chaparral watershed in southern California and documented during a period without rain a return to pre-fire repellency approximately 2 months after a fire. They also observed similar variability in water repellency at the 10 cm scale and watershed-scale. Flashier discharge did occur at burned sites in our study throughout WY2005, especially in early season storms. However, the closely spaced storms and above average precipitation for WY2005 diminished the fire-related impact on total discharge as the season progressed.

As indicated in Figure 3, a difference in runoff coefficients between burned and unburned sites was evident in the early season storms with the values at San Onofre five to seven times greater than at Rattlesnake and three times greater than at Arroyo Hondo. This post-fire response is similar to Sinclair and Hamilton's (1955) findings of a three to five times increase during the first few post-fire storms in a SDEF watershed.

Fire-related reductions in evapotranspiration and infiltration capacity were overshadowed during two series of large storms from 7 to 11 January 2005 and 17 to 22 February 2005. These two series of storms had up to 46 and 31 cm of precipitation, respectively, which exceed the average soil storage capacity in the region, estimated to be 10 cm for an average soil thickness of 1 m by Beighley *et al*. (2003). As soils approached or reached saturation during these large storms, the runoff coefficient increased in both burned and unburned watersheds (Figure 3), reducing the role of fire-related increases in discharge. By the end of end of the rainy

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season, the difference in runoff coefficients at San Onofre, Arroyo Hondo, and Rattlesnake watersheds was less than 15% (0.34, 0.40, and 0.36, respectively).

In comparison, Loaiciga *et al.* (2001) reported up to 20 to 30% increases in post-fire annual stream flow for a southern California chaparral watershed that was partially burned. The full WY2005 results from San Onofre watershed also differ from a threefold annual runoff increase for moderately burned and 14-fold increase for severely burned SDEF chaparral watersheds during a post-fire year with average precipitation (Riggan *et al.*, 1994).

The burned Arroyo Hondo subcatchment had peak instantaneous discharges approximately 200 times greater than those in the unburned subcatchment on 31 December 2004 and 26 January 2005. Sinclair and Hamilton (1955) and Riggan *et al.* (1994) found peak discharges to increase 128 times and 300 times, respectively, in SDEF watersheds impacted by fire. The increased runoff response and peak discharges were likely enhanced by hydrophobic soil layers formed during the fire. As the season progressed, hydrophobic layers were penetrated by rill erosion, as described by Wells (1987), and a greater portion of the soil storage capacity was available resulting in relatively lower peak flows.

Sediment export

High suspended sediment concentrations measured during early season storms with low discharge are consistent with the sediment mobilization process of thin debris flow formation caused by hydrophobic soils (Wells, 1987; Gabet, 2003). During this period, significant amounts of sediment were deposited in the lower Gaviota channel. As the penetration of hydrophobic layers led to reduced hillslope surface erosion and the carrying capacity of runoff increased with significant runoff contribution from the unburned upper Gaviota catchment, sediment deposited in the channel during early season storms was moved downstream. The pattern of deposition followed by erosion is consistent with the observations made by Florsheim *et al.* (1991), but differs from WY2005 observations in the almost completely burned San Onofre watershed, where large storms occurring from late December through February continued to convey elevated amounts of suspended and bed load (up to 1 m boulders).

The change in WY2005 discharge-concentration relationships for suspended sediment seen at HO00 (Figure 4(c)) imply that the bulk of Arroyo Hondo's WY2005 suspended sediment export comes from post-fire erosion. Most of the sediment generated from thin debris flows during early season storms in the Arroyo Hondo watershed was conveyed out of the catchment during the late December 2004 storms. The two late December 2004 storms accounted for 50% of the total WY2005 suspended sediment export at HO00, yet accounted for only 10% of the WY2005 runoff. The occurrence of clockwise hysteresis during the late December storms (Figure 4(c)) suggests that the suspended sediment came from sources near the channel (Seeger *et al.*, 2004). Peak discharges during late December storms were exceeded three times from WY2003 to 2004, indicating that channel deposits subject to erosion at these discharge rates would have already been removed. HO00 suspended sediment concentrations returned to near pre-fire levels during the large storms from 7 January to 22 March 2005, even though peak discharges at HO00 during the 7–11 January and 22 March 2005 storms were nearly double those measured for the late December 2004 storms.

Suspended sediment export from the burned San Onofre watershed of 181 mt ha^{-1} is substantially higher than that in unburned and partially burned chaparral watersheds under most conditions. Warrick (2002) estimated average annual sediment export of 15 mt ha^{-1} for unburned Santa Ynez watersheds and 27 mt ha^{-1} for the Gaviota watershed. Inman and Jenkins (1999) found that average suspended sediment export from unburned watersheds in the Transverse Ranges for the period from 1969 to 1995 to be 12 mt ha^{-1} but estimated of 157 mt ha^{-1} from the Santa Ynez Range during 1969, a year with exceptional runoff. Similarly, Warrick *et al.* (2012) reported sediment export of 110 mt ha^{-1} in the exceptionally wet winter of 1978 that followed a fire in 1977 that burned the Arroyo Seco watershed in central California.

Nutrient biogeochemistry and fluxes

Ammonium and DON were the primary forms of N in burn-impacted streams early in the wet season. Later in the winter, ammonium concentrations declined, whereas nitrate concentrations increased. The transition in dissolved nitrogen constituents occurs because of a combination of changes in hydrologic, erosional, and biogeochemical processes. Following a fire in chaparral, Christensen and Muller (1975) reported losses of nitrate in the upper soil layer because of volatilization, but found additions of nitrogen in the form of ammonium and DON deposited as ash on the soil surface. Ammonium levels can increase by two to three times within the upper 5 cm of soil following fire (Christensen and Muller, 1975; Riggan *et al.*, 1994), and Debano *et al.* (1979) suggested that the ammonium is produced as amino acids in the soil and litter are destroyed by heat.

With microbial activity limited by low soil moisture, high levels of ammonium and DON and low levels of nitrate are expected to remain until soils are wetted by the first rains. Storm runoff during the early season rains at the burn sites was accompanied by thin debris flows that entrained the high levels of ammonium and DON present on the soil surface and in the upper soil layer.

After wetting of soils, nitrification of ammonium resulted in increased nitrate concentrations. By late December, nitrate concentrations reached their annual peak, whereas ammonium and DON VWM concentrations dropped one to two orders of magnitude over the remainder of the season's storms. Nitrate export comprised 85 to 95% of total dissolved nitrogen export from San Onofre watershed compared with 67 to 88% from Rattlesnake watershed for the large storms between late December 2004 and March

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2005. In Mediterranean-type climates, mineralization of organic nitrogen and subsequent nitrification of ammonium are triggered by early season storms that wet soils and initiate decomposition of organic matter by microbes (Schlesinger, 1997). Large winter storms will then leach nitrate from soils, resulting in peak nitrate concentrations after the hydrograph peak (Riggan *et al.*, 1985). Fire enhances these processes by increasing levels of organic nitrogen and ammonium in soils and by changing the soil pH. The addition of base cations from ash deposition can increase the soil pH (Wells *et al.*, 1979) leading to increased nitrification (Schlesinger, 1997). Following the initial wetting of soils from early season storms, Christensen and Muller (1975) found that nitrate concentrations in soils rose and remained high for the 2 years of their study, and they attribute these high nitrate concentrations to nitrification of the elevated levels of ammonium produced by fire because most of the nitrate in the upper soil layer was lost to volatilization.

Ammonium flux increased significantly in fire-impacted catchments. WY2005 ammonium export from the burned portion of the San Onofre watershed was seven to eight times higher than from urban and agriculture land uses and 39 times higher than from undisturbed chaparral. In contrast, although nitrate export from San Onofre increased as a result of fire by 5.5 times compared with Rattlesnake watershed and was four times greater than that from an urban watershed, nitrate export from an agricultural watershed was three times higher than from burned chaparral. However, the increase in nitrate export from San Onofre watershed is less than the nine times increases in nitrate exported from burned chaparral catchments subject to high levels of atmospheric nitrogen deposition (Meixner *et al.*, 2006).

Ash deposition is generally the main source of increased phosphate levels detected in burn-impacted chaparral soils (Debano and Conrad, 1978), and is the likely source that was later mobilized by early season, thin debris flows in the San Onofre and Gaviota watersheds. Although Christensen and Muller (1975) found phosphorous concentrations to double in the upper 6 cm of burned chaparral soils, water soluble phosphate accounted for only 1% of total phosphorous. Phosphate concentration patterns mimicked the hydrograph suggesting that phosphate was mobilized along with suspended sediments, rather than being leached from soils as readily as nitrate.

Phosphate export from Rattlesnake and Arroyo Hondo watersheds was similar in WY2003 and 2004, but after the fire in WY2005, phosphate export of 24 mol ha^{-1} from San Onofre and Arroyo Hondo watersheds was twice as high as from Rattlesnake watershed. Phosphate export from Gaviota watershed in WY2005 was nearly three times higher than San Onofre and Arroyo Hondo watersheds and over six times greater than Rattlesnake watershed. Because annual phosphate VWM concentrations at the site in the Gaviota watershed above the burned portion were only 8% lower than at the site below the burned portion, the predominant source contributing to increased export from Gaviota watershed was the upper, unburned portion of the catchment. Differences in geology (Dibblee, 1988b) and accelerated erosion rates because of conversion from native coastal sage and chaparral to grass rangelands (Warrick, 2002; Gabet and Dunne, 2003) are likely causes of the Gaviota watershed's relatively elevated export of phosphate.

CONCLUSIONS

The above average precipitation for WY2005 provided an opportunity to measure hydrologic and biogeochemical responses to fire during one of the wettest years on record. Storm runoff and peak discharge increase in burned compared with unburned sites were greatest during early season storms when enhanced runoff generation occurred. As the winter progressed, closely spaced storms and above average WY2005 precipitation reduced the fire-related impacts that resulted in significant increases in annual post-fire runoff in other studies in southern California chaparral (Riggan *et al.*, 1994; Loaiciga *et al.*, 2001). Total suspended sediment export of 181 mt ha^{-1} from 82% burned San Onofre watershed was approximately an order of magnitude greater when compared with similar unburned watersheds. Other studies of annual post-fire sediment export from southern California chaparral watersheds estimated sediment trapped in debris basins or deposited in the stream channel (Keller *et al.*, 1997) but did not measure suspended sediment export. Ammonium, nitrate, DON, and phosphate WY2005 export increased in burned southern California chaparral watersheds when compared with unburned watersheds. Ammonium had the greatest increase with the highest export occurring during the early season ash-laden storm runoff. Nitrate increased in burned watersheds by 5.5 times compared with unburned watersheds and comprised 84% of total dissolved nitrogen export from San Onofre watershed. Fire-related changes in ammonium and nitrate concentration patterns were similar to those found in chaparral watersheds subject to chronic atmospheric N deposition in the SDEF, but the 40 times increase in annual nitrate export was much greater in SDEF burned watersheds. DON and phosphate export from the burned watershed increased by 2.8 and 2 times, respectively, when compared with an unburned chaparral watershed.

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