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ORIGINAL RESEARCH

Analysis of the impacts of the Soberanes Wildfire on stream ecosystems

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Wildfires within the western United States are expected to increase in frequency and magnitude but our understanding of how they impact coastal streams is limited. The 2016 Soberanes Wildfire provided an opportunity to determine which biotic and abiotic factors were most impacted by the fire occurring on the California Central Coast. Water quality, benthic macroinvertebrate samples and habitat measurements were taken both before and after the fire. We observed an increase in the levels of phosphorus 4 months and 8 months post-fire which may have contributed to observed increases in microalgae growth. There was a complete loss of shredders in the benthic macroinvertebrate community which could be caused by the loss of vegetation in stream-adjacent riparian areas. These post-fire results were expected based on previous research, however organic material inputs to the stream unexpectedly did not change between pre- and post-fire conditions, which may be due to a delayed increase in inputs from riparian vegetation which short-term monitoring is unable to capture. A long-term monitoring program effort is critical for understanding the recovery of these coastal watersheds from fire.

Key words: abiotic, benthic macroinvertebrates, biotic, coastal watersheds, water quality, wildfire

Areas burned by wildfires are expected to increase dramatically due to the changing climate. Specifically, fire frequency and burned areas are predicted to increase in the western United States due to predicted warmer summers and reduced levels of precipitation (Sankey et al. 2017; Westerling et al. 2011). Brown et al. (2008) estimated that about 65% of the water supply in the western United States originates in watersheds that contain fire-prone vegetation, making these watersheds even more important to understand (Sankey et al. 2017). The burning of watersheds is known to impact downstream aquatic ecosystem, infrastructure, recreational use, water supply and water quality (Marina et al. 2019; Hallema et al. 2018; Sankey et al. 2017; Gresswell 1999).

In general, our understanding of how coastal streams recover from wildfires in Mediterranean climates is limited. These coastal watershed experience additional factors that in-land watersheds may not such as greater salt deposition, greater fog influence and greater numbers of biologically isolated organisms. Wildfires are known to impact all aspects of a stream (i.e., hydrological, geochemical, and biological) so understanding the holistic picture of these watershed ecosystems post-wildfire is critical for managing both water resources and biodiversity in California. Although recent work has provided a better understanding of particular impacts of fire on stream ecosystems (summarized by Bixby et al. 2015), more holistic examinations of the effects of fires in Mediterranean systems are still needed.

In 2016, the Soberanes Wildfire burned large areas within Monterey County and Los Padres National Forest, but it also provided a natural, large-scale experiment on the effects of fire on coastal watershed streams and ecosystems. The availability of historical biological and chemical monitoring data from this area within the Central Coast allowed us to compare conditions pre and post-fire.

Our objective was to determine the extent to which abiotic factors (e.g., nutrients, sediments, and other physical aspects) and biotic factors (algae and benthic macroinvertebrates) were impacted by the Soberanes Wildfire. We predicted that nutrients such as a phosphate and nitrate will increase post-fire similarly to other research (Bixby et al. 2015; Diemer et al. 2015; Sherson et al. 2015). Additionally, previous studies indicated that there may be an increase erosion and sediment inputs, transport and deposition which we expect to see as an increase in finer sediments (Cooper et al. 2015). Finally, we expected benthic macroinvertebrates to decrease in abundance post-fire due to increases in sediment deposition, but algae might increase due to increased nutrients.

METHODS

Study area

The Soberanes Wildfire burned throughout the California Central Coast and within the Garrapata State Park and the Los Padres National Forest (Figure 1). Burn intensities varied considerably among the coastal and inland watersheds. For this study, we focused on a few specific coastal watersheds because of their importance to threatened west coast steelhead which rely on some of these coastal streams for reproduction and rearing habitat (NMFS and NOAA 2000). The coastal watersheds of Garrapata Creek (36.417°N, -121.914°W) and Soberanes Creek (36.455°N, -121.923°W) had most of their watershed areas burned in the fire and were the primary focus of this data analysis effort (Figure 1, Table 1). Geomorphological data from three other coastal watersheds are also presented (Table 1). Watersheds examined ranged in size with the Big Sur River Watershed having the largest area of approximately 60 square miles. However, the watersheds supporting Garrapata Creek and Soberanes Creek were more representative of the small watersheds typical of the Central Coast, with watershed areas of 27.7 and 8.0 km^2, respectively.

All watersheds in the study comprised mostly natural land cover with low amounts of agriculture. Prior to data collection, sites were selected based on the US Forest Service Burned Area Emergency Response Team soil burn severity (USFS BAER Team 2016) and low landscape variability (e.g., only small difference in elevation). We calculated the percent of high, medium, and low soil burn severity for all coastal watersheds in the study area that had published pre-fire chemical, physical, or biological data and sites were chosen from across this range of burn severity. For example, Garrapata Creek and Soberanes Creek were both burned to similar extents, with approximately 86 and 83 percent of each watershed burned, respectively. Other watersheds varied in the proportion burned such as Limekiln

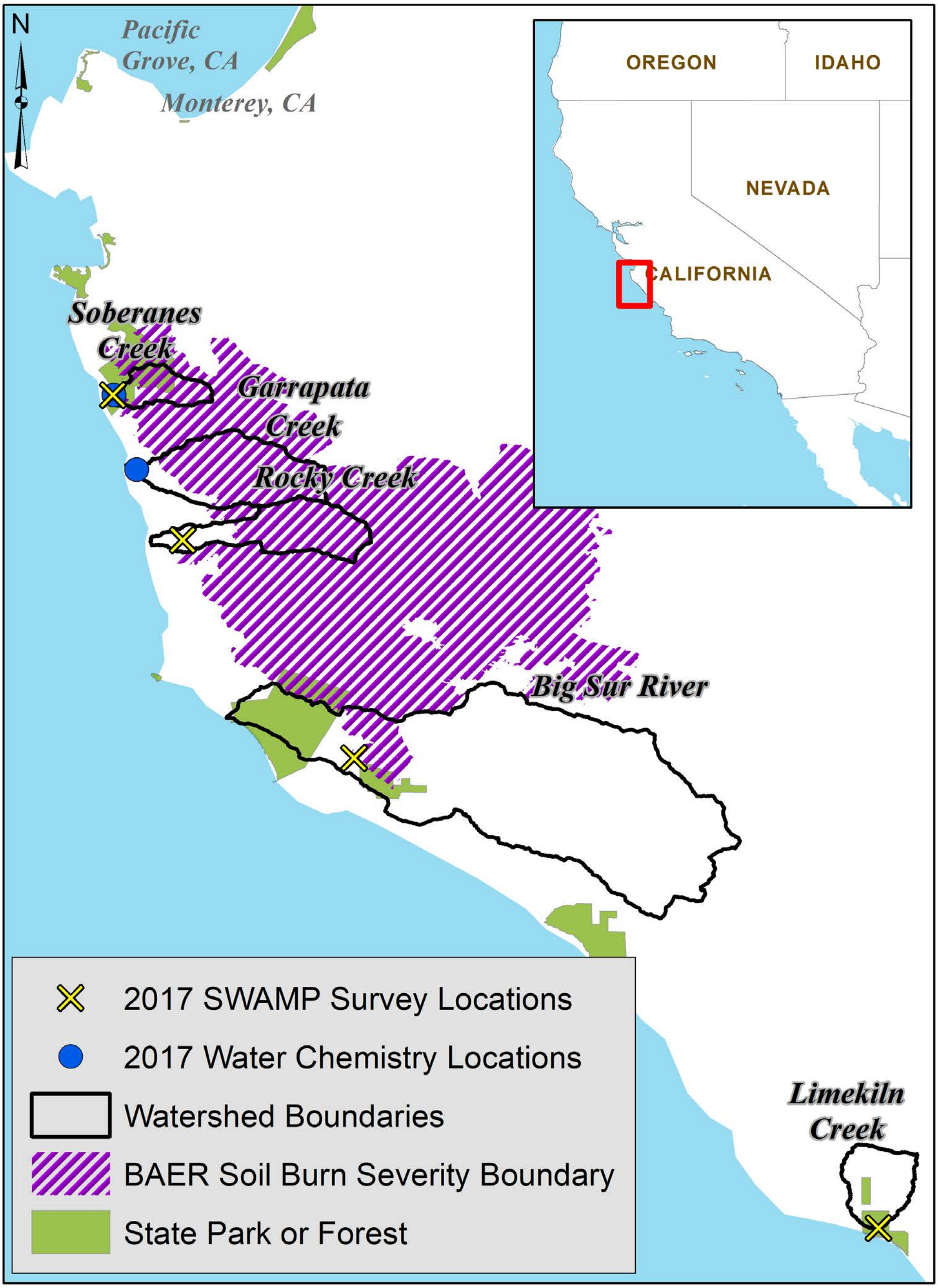

Figure 1. Map representing sites where SWAMP surveys were completed as denoted by 'X' and where water chemistry samples were taken denoted by blue circles. Soberanes Creek Watershed and Garrapata Creek Watershed are symbolized on the map from North to South, respectively.

Table 1. Coastal watersheds analyzed by abiotic or biotic factors.

Watershed	Biological	Water Chemistry	Geomorphological
Soberanes Creek	X	X	X
Garrapata Creek		X	
Limekiln Creek			X
Big Sur River			X
Rocky Creek			X

Creek which was unburned and served as our control site. Verification of these watershed delineations were done using known watershed boundaries from the U.S. Geological Survey National Hydrography Dataset (USGS 2017) . Post-fire measurements were made in the vicinity (within 100 m) of the pre-fire data, which was downstream of the portion of the watershed burned in all cases.

Spatial watershed methods

To supplement field measurements taken at these coastal streams, we also delineated watersheds and used datasets acquired from the USEPA StreamCat for each of our sites using ESRI ArcGIS and R (Hill et al. 2016; Environmental Systems Research Institute, Inc., Redlands, CA, USA; R v.3.6.1, www.r-project.org, accessed Jun 2017; Appendix I). The StreamCat datasets are watershed summaries of natural variables that influence stream conditions (e.g., geology, topography, soils, vegetation, and climate; Hill et al. 2016). Watershed summaries not available in the USEPA StreamCat were created using various geospatial datasets such as Landfire's fuel models, USGS National Map and PRISM Climate Group and calculated their zonal statistics (Appendix I). Some of these predictor watershed summaries included identification of potentially high erosion areas, year since last wildfire, and estimated valley slopes (Appendix I). At burned sites, we also added the summarized severity and extent of the burn at the watershed scale calculated previously during site selection.

Abiotic methods

We collected water quality samples for analysis of nitrate and phosphate concentrations at Garrapata Creek and Soberanes Creek weekly from October 2016 until March 2017 (Figure 1, Table 1). At each site, we collected metadata such as time and water temperature. We placed all water quality samples on ice until they could be processed (within 24-hours of collection). In the laboratory, a Hach colorimeter (accuracy ±0.03 mg/L for nitrate, ±0.06 mg/L for phosphate) was used for all samples to measure phosphate and nitrate concentrations (mg/L). We obtained measurements of phosphate, nitrate, and water temperature collected by other regional research and monitoring efforts from California Environmental Data Exchange Network (CEDEN) (State Water Resources Control Board 2020.). Visualization and comparison of phosphate, nitrate and water temperature were done using R (R v.3.6.1, www.r-project.org). From CEDEN, Soberanes Creek had water chemistry data for two years (2000 and 2016) and Garrapata Creek had data for four years (2002, 2003, 2009 and 2015) before the fire.

Surface Water Ambient Monitoring Protocol (SWAMP) surveys were completed within four coastal watersheds post wildfire in the summer of 2017 (i.e., Soberanes Creek, Rocky Creek, Big Sur River and Limekiln Creek; Table 1) following the reach wide benthos protocol (Ode et al. 2016). We collected physical habitat measurements such as substrate size using the Wolman 'pebble count' technique which allows the collector to calculate the percentiles of particle size (Ode et al. 2016). We then compared our data to previous SWAMP data available through CEDEN.

We constructed generalized linear models (GLMs) in R (R v.3.6.1, www.r-project.org) to examine the influence of natural factors and fire on the size of river, and percent fine sediment (% of substrate less than 2 mm in diameter) were calculated from SWAMP field measurements. Predictor data were developed from the spatial watershed metrics mentioned previously (i.e., StreamCat datasets, supplemental zonal statistics). The natural factors we used as potential predictors of sediment size are detailed in Appendix I and include 9 geology/soil variables, 5 hydrology variables, 4 topography variables, and 26 vegetation variables. GLMs can suffer over fitting if too many predictors are used, so we used stepwise Akaike information criterion (AIC) regression methods to select the model with predictors that best fit the data (Pleog et al. 2014). These models were created from a dataset of other coastal streams that included Garrapata and Soberanes Creeks (n = 9).

Biotic methods

While physical habitat measurements were being taken at each transect following the SWAMP standard operation procedures (Ode et al. 2016), we recorded microalgae thickness class observations at each substrate size class measurement. Following Ode et al. (2016), classes are defined as: class 0- no microalgae present, class 1- present, but not visible (i.e., can be felt but not seen), class 2- < 1 mm, class 3- 1-5 mm, class 4- 5-20 mm, and class 5- > 20 mm.

At each SWAMP location, we collected benthic macroinvertebrates at 11 transects 15-m apart over a 150-m sampling reach. A 500-µm mesh D-frame net was used to collect benthic macroinvertebrates in the immediate 0.09 m^2 area in front of the net (Ode et al. 2016). Incidental vertebrates collected were immediately released, and collected invertebrates were stored in 70% ethanol for later identification in the lab (Ode et al. 2016).

These invertebrate samples were only processed in part for Soberanes Creek for two predominantly sensitive taxonomic orders, Ephemeroptera (Mayfly) and Plecoptera (Stonefly) due to available time and funding. Due to the diversity in life cycle traits and sensitivity to disturbance at the genus level, these two orders may provide sufficient information for understanding how diversity within genera and functional feeding groups may respond to fire disturbance (Merritt and Cummings 1996; Buss et al. 2007; Rosenberg et al. 1993). Both orders are known to be sensitive to changes in sediment or water quality and are therefore commonly used in the detection of water quality changes (Merritt and Cummins 1996; Buss et al. 2007; Rosenberg et al. 1993). Previous benthic macroinvertebrate samples were collected prior to the fire in 2010 and 2016 at Soberanes Creek which were available through CEDEN. Post-fire samples were collected by students at California State University, Monterey Bay (CSUMB) about four months post-fire (February 2017), and again eight months post-fire (June 2017) by members of the Watershed Environments and Ecology lab at CSUMB. These datasets provide the time series for analyses reported here. We compared the counts of individuals by order and by functional feeding groups, and diversity calculated using the Shannon diversity index (Shannon 1948) from before and after the fire associated (Hughes 1978; Lydy et al. 2000).

RESULTS

Abiotic results

Phosphate increased after the wildfire at Soberanes Creek and Garrapata Creek, however nitrate and water temperature had minimal change or remained constant (Figure 2 and Figure 3). In addition, no change was observed for coarse particulate organic matter (CPOM) or wetted width measurements at these two sites.

At the four sites we sampled using the SWAMP protocol, the percent of fines are consistent but dramatically increased around June of 2017, and the D_{15} decreased over time

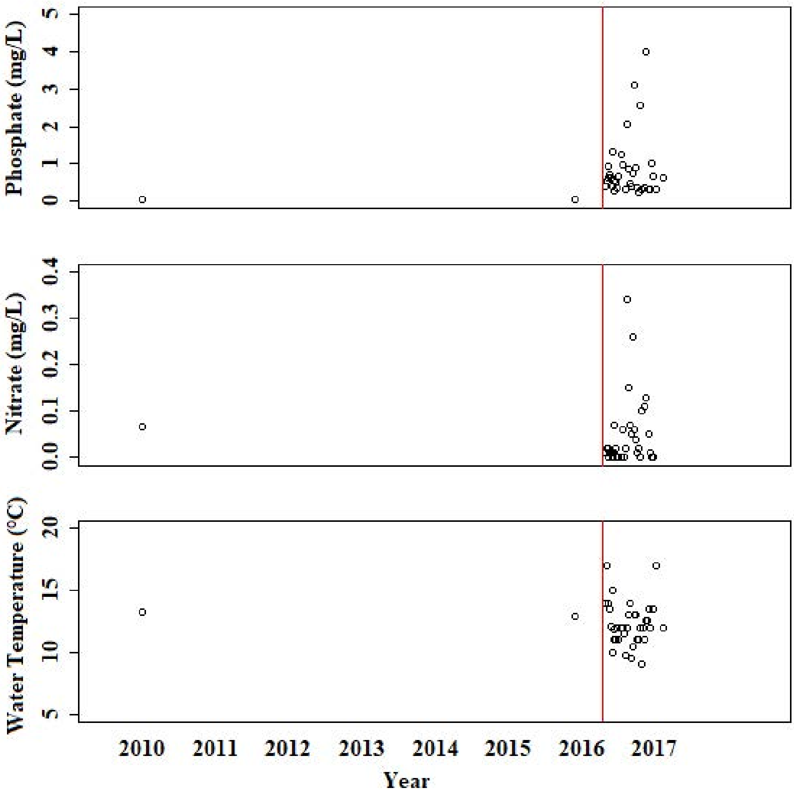

Figure 2. Data points represent water chemistry samples including water temperature, nitrate and phosphate from Soberanes Creek, pre-fire (before the event point in red) and post-fire. An outlier was removed from this figure which represented Soberanes Creek water quality data where on 20 January 2017, there was a phosphate measurement of 15.1 mg/L.

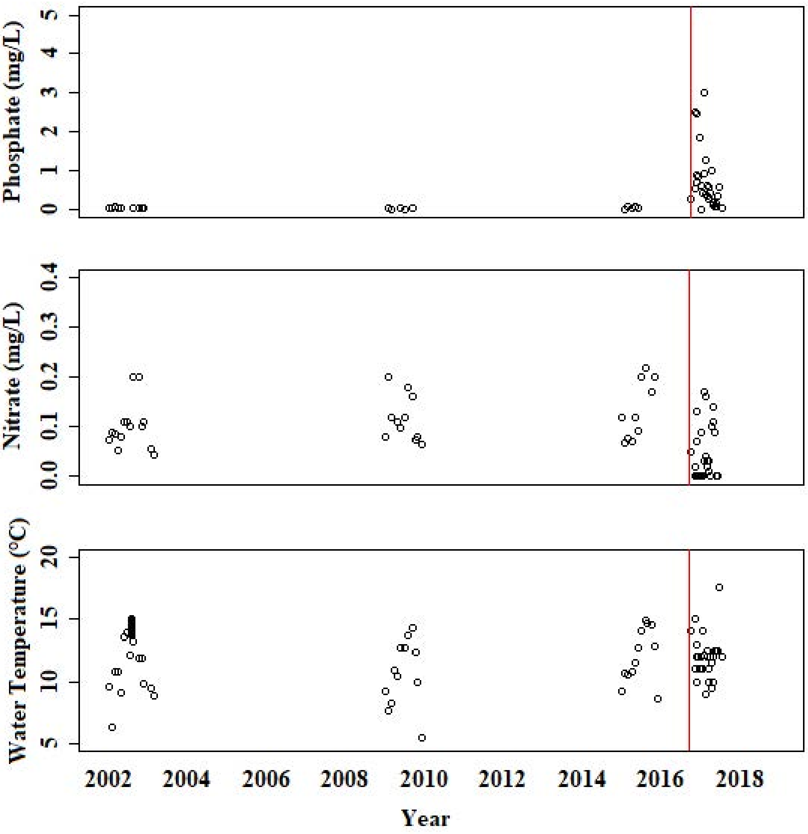

Figure 3. Data points represent water chemistry samples of water temperature, nitrate and phosphate taken at Garrapata Creek, pre-fire (before the event point in red) and post-fire.

(Figure 4). In addition, D_{50} and D_{84} remained constant then decreased in June of 2017 (Figure 4). All of the GLMs relating variation in sediment size distributions in coastal streams to environmental factors contained significant predictors and explained the majority of variation in sediment sizes (r^2 values 79%-90%; Table 2). The percent fine sediment model explained 90% of model variation, including the same factors as the other models, but also factors representing natural variation (i.e., average temperature change from 1981-2010, year since last fire, previous year's average precipitation and percentage of clay in the watershed). We examined the partial dependence plots to determine how each predictor variable influenced percent fines (Figure 5). Percent fines decreased as average temperature, percent of clay substrate in watershed, and years since last fire increased. The opposite pattern is seen for average precipitation for the year prior to SWAMP survey, as the precipitation increases the percent of fines increased.

Table 2. Results of GLM models for river sediments response data. Significance represented as <0.001:***, <0.01:**, <0.05:*

Models	R^2	AIC
D15~Average Temperature (1981-2010)+Years Since Last Fire***	93%	56.7
D50~ Average Temperature (1981-2010) + Year Since Last Fire***	90%	79.0
D84~Average Precipitation (1981-2010) + Average Elevation* + Year Since Last Fire**	79%	100.8
Percent Fines~ Average Temperature (1981-2010)*+Year Since Last Fire**+Previous Years' Precipitation + Percent Clay in Watershed	90%	63.5

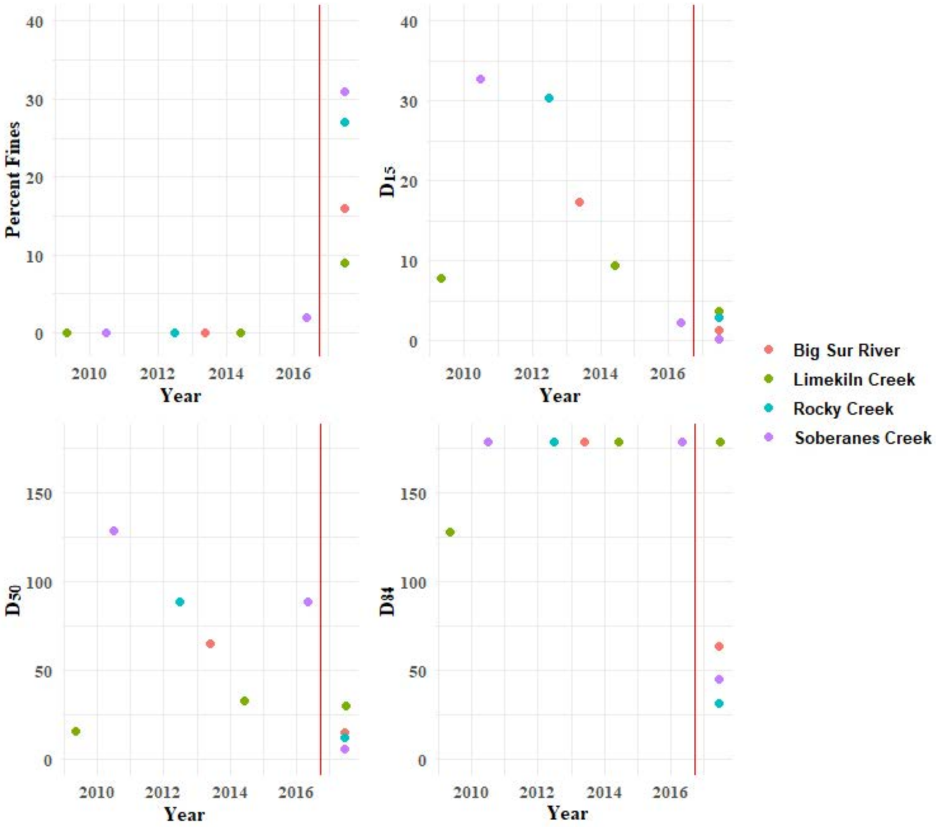

Figure 4. Changes in particle size D_{15} (where 15% of total sample is smaller than this size), D_{50} (where 50% of total sample is smaller than this size), D_{84} (where 84% of total sample is smaller than this size), and percent of fines at the four SWAMP survey locations.

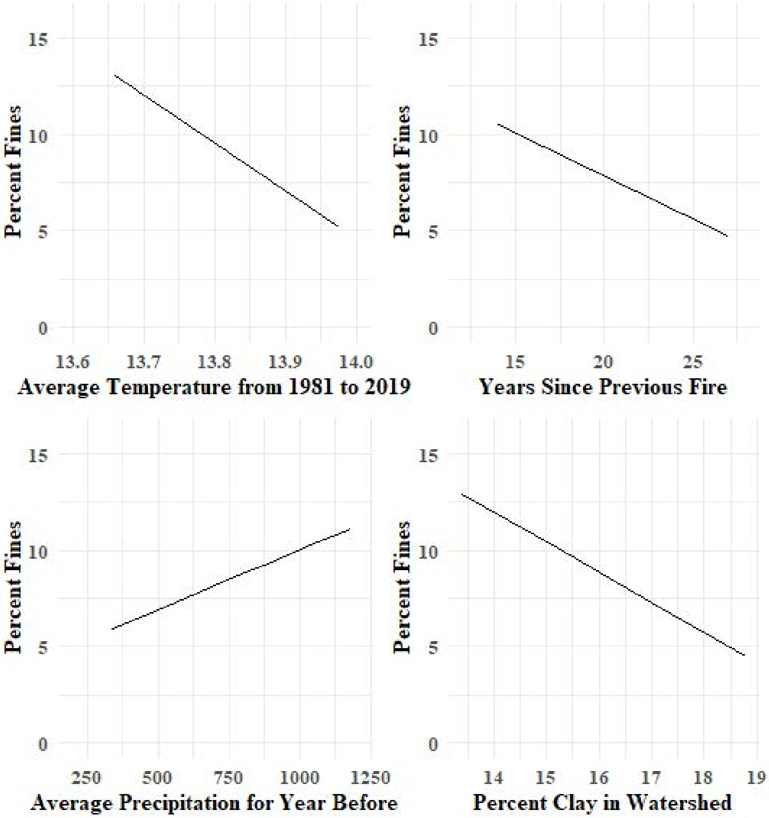

Figure 5. Partial dependence plots of the percent fine sediment generalized linear model predictors.

Biotic results

Microalgae thickness classes increased post-fire at Soberanes Creek, Big Sur River and Rocky Creek (Figure 6). Limekiln Creek (control site) had the greatest microalgae thickness before the wildfire but also showed increased thickness post-fire (Figure 6). There were greater abundances of Ephemeroptera and Plecoptera before the fire in 2010 and 2016 compared to four months and eight months post fire (269, 234, 36, 148 combined counts, respectively). An increasing trend is shown from four months to eight months post fire potentially indicating a recovery in abundance of Ephemeroptera (Figure 7).

Before the fire, functional feeding groups for these two orders mainly contained collectors, scrapers, shredders, and a small number of predators (Figure 8). However, four months post fire, where there was a noticeable loss in abundance of organisms (Figure 7), and a decline in counts for all functional feeding groups. At eight months post fire, there was an increase in abundance of collectors and predators, however no shredders have collected (Figure 8). From June of 2010 to June 2017, there was also a slight but continuous decrease in the scraper functional feeding group (16, 9, 6, 3 chronologically, Figure 8).

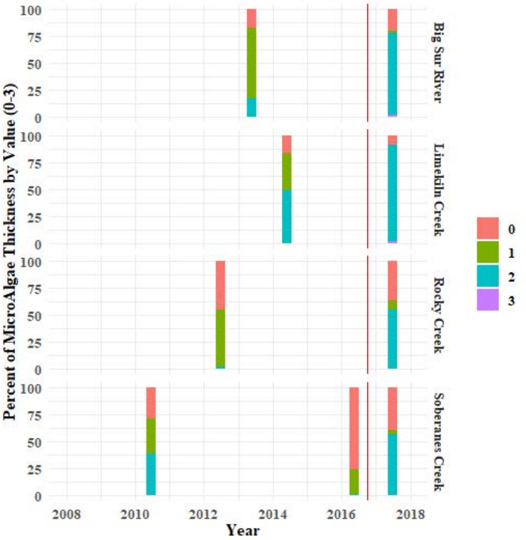

Figure 6. Pre and post fire thickness classes of microalgae on rocks at SWAMP survey sites. Microalgae thickness classes: 0- no microalgae present, 1-present, but not visible, 2-greater than 1 mm, and 3-1–5 mm.

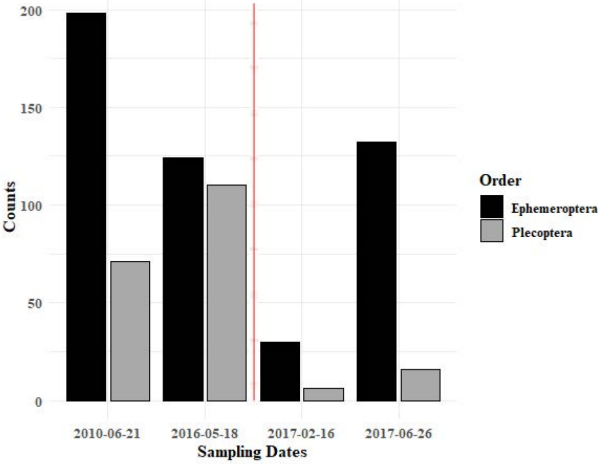

Figure 7. Pre and post abundance results for the two orders of concern. Red line represents the Soberanes Wildfire start event in October of 2016.

Genus level Shannon diversity index scores range from about 1.5–2 before the fire, to 0.9–2.1 after the fire (Figure 9). There was little change in diversity immediately after the fire, but later that year we observed a decrease.

DISCUSSION

We expected nutrient concentrations to increase, as nitrogen and phosphorus are often mobilized by fires (Bixby et al. 2015; Diemer et al. 2015; Sherson et al. 2015). We did not observe any change in nitrate concentrations post-fire but did see the expected increases in phosphorus. The post-fire increases in phosphorus we observed at Garrapata and Soberanes Creeks (Figures. 2 and 3) may be caused by two mechanisms. The increase in phosphorus could be due to a decrease in surrounding vegetation taking up nutrients. Alternatively, it

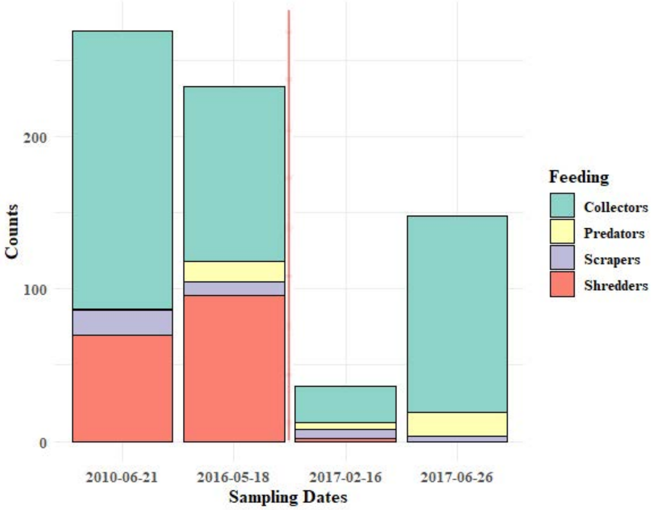

Figure 8. Pre and post functional feeding groups by count of organisms. The two sample dates before October 2016 represent data available on CEDEN. Post-fire data is represented in the two bars right of the red line.

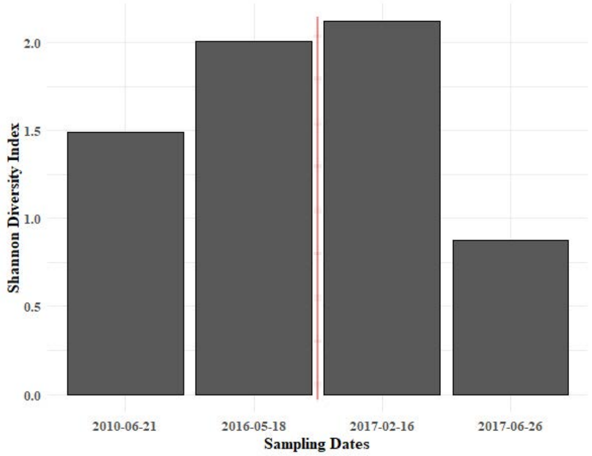

Figure 9. Pre and post wildfire, genus level Shannon diversity index scores for each sample timeframe. Red line represents the Soberanes Wildfire start event in October of 2016.

may also be due to increased phosphorus-enriched sediments in the water. Both Garrapata and Soberanes Creek's watersheds had areas greater than 80% burned and could be experiencing one or both mechanisms. At Soberanes Creek post-fire we observed an increase of fine sediments (Figure 4) which indicates increased erosion of the surrounding watershed due to wildfire. Increasing bioavailable phosphorus from phosphorus-enriched sediments is known to be a key mechanism that impacts streams and large watersheds (Emelko et al. 2015). Diemer et al. (2015) showed that fires in boreal forests alter stream chemistry for many years after by altering the retention of nutrients in streams. The legacy this increase in bioavailable phosphorus may have downstream is still unknown but long-term monitoring may be able to explain the recovery or long-term impacts of this change.

Increases in nutrient concentrations can also lead to changes in algal response, specifically increases in phosphorus in post-fire settings are known to increase algal biovolume (Klose et al. 2015). Increased light could also increase algae (Cooper et al. 2015, Coombs and Melack 2013), but because we measured algae below where the fire affected the stream, light was not changed between before and after the fire. We saw an increase in microalgae thickness at all sampled creeks and rivers post-fire (Figure 6) which could indicate that the increase in nutrients is contributing to an increase in microalgae growth. Microalgae thickness also increased post-fire in the unburned watershed, but this watershed had the greatest microalgae thickness pre-fire which could be due to previous fires in the region such as the Chalk Fire which occurred in 2008. Algal levels are known to be higher in streams post-fire where riparian vegetation has burned (Cooper et al. 2015). This increase in algae growth could impact stream food webs and basal resources (Cooper et al. 2015). It should be noted that algal growth after fires depends on many factors such as sediment deposition, light availability, canopy cover, and flooding so not all algal growth could be attributed to the increase in nutrients (Coombs and Melack 2013).

We expected that as microalgae increased we would see a corresponding increase in the amount of benthic macroinvertebrates belonging to the scraper functional feeding group. However, our results indicate a decrease in the number of scrapers post-fire (Figure 7), which may be due to other factors such as increased fine sediment deposition (Jones et al. 2012). We also found a complete loss of shredders post-fire which could be attributed to a decrease in vegetative inputs from the riparian communities. Similar to the results of Rodríguez-Lozano et al. (2015), we saw a recovery of most functional feeding groups within a year post-wildfire. However, we did not see the shredders feeding group recover in the first year.

Although nitrate concentrations and organic inputs such as CPOM are also reported to respond to fire, we did not see changes in levels of either nitrate or CPOM post-fire. CPOM may increase post-fire with pulses of leafy matter or decrease as materials get mobilized and transported downstream (Copper et al. 2015, Beakes et al. 2014; Britton 1990). Robinson et al. (2005) and Bendix and Cowell (2015) noted that riparian tree damage and organic inputs may take many years after a fire to fall into rivers, so we may not have captured changes in CPOM in the first year of post-fire monitoring. Nitrogen released post-fire may have been taken up by the increasing microalgal biomass, indicating that these coastal streams are normally nitrogen limited (Feminella et al. 1989).

Overall, we determined that phosphorus concentrations, the amount of fine sediments, the composition and abundance of the benthic macroinvertebrate assemblage, and amounts of microalgae are the factors in coastal streams most affected by wildfire. Additional monitoring is needed to determine when all of the abiotic and biotic factors have fully recovered. In the future, long-term post-fire monitoring of all aspects of streams should be planned for and resourced to determine if the same impacts we observed occur and how fast streams recover. Other natural events such as drought may be exacerbating stress on these streams and watersheds and incorporating them in future work is critical to deepening our understanding of the impacts caused by fire.

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Author Contributions

Conceived and designed the study: JD, JO, and MB
Collected the data: MB and JD
Performed data analysis: JD
Authored the manuscript: JD and JO
Provided critical revision of the manuscript: all authors

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APPENDIX I

Predictor Variables	Source	Description
A__SB2	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Moderate load activity fuel or low load blowdown, 7-12 t/ac, 0-3 inch diameter class, depth about 1 foot, blowdown scattered with many still standing, spread rate and flame low
A__TL5	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: High load conifer litter, light slash or dead fuel, spread rate and flame low
BFIWs	USEPA StreamCat	Baseflow is the component of streamflow that can be attributed to ground-water discharge into streams. The Baseflow Index (BFI) is the ratio of baseflow to total flow, expressed as a percentage, within watershed.
CaOWs	USEPA StreamCat	Mean % of lithological calcium oxide (CaO) content in surface or near surface geology within watershed
ClayWs	USEPA StreamCat	Mean % clay content of soils (STATSGO) within watershed
CompStrgthWs	USEPA StreamCat	Mean lithological uniaxial compressive strength (megaPascals) content in surface or near surface geology within watershed
DamDensWs	USEPA StreamCat	Density of georeferenced dams within watershed (dams/ square km) based on the National Inventory of Dams (https://catalog.data.gov/dataset/national-inventory-of-dams)
ElevWs	USEPA StreamCat	Mean watershed elevation (m)
GR1	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Short, sparse dry climate grass is short, naturally or heavy grazing, predicted rate of fire spread and flame length low
GR2	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Low load, dry climate grass primarily grass with some small amounts of fine, dead fuel, any shrubs do not affect fire behavior
GS1	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Low load, dry climate grass-shrub shrub about 1 foot high, grass load low, spread rate moderate and flame length low
GS2	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Moderate load, dry climate grass-shrub, shrubs are 1-3 feet high, grass load moderate, spread rate high, and flame length is moderate
HighSqKm	BAER Soil Burn	% of watershed area with high burn soil severity
LowSqKm	BAER Soil Burn	% of watershed area with low burn soil severity
MaxRelief	USGS National Map	Using the 30-meter resolution DEM from National Map, max relief was calculated by taking the max elevation from the minimum elevation

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Predictor Variables	Source	Description
ModSqKm	BAER Soil Burn	% of watershed area with moderately burn soil severity
NB1	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Non Fuel Vegetation: Urban
NB3	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Non Fuel Vegetation: Agriculture
NB8	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Non Fuel Vegetation: Water
NB9	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Non Fuel Vegetation: Barren
OmWs	USEPA StreamCat	Mean organic matter content (% by weight) of soils (STATSGO) within watershed
PctConif2011Ws	USEPA StreamCat	% of watershed area classified as evergreen forest land cover (NLCD 2011)
PctDecid2011Ws	USEPA StreamCat	% of watershed area classified as deciduous forest land cover (NLCD 2011)
PctFire2000Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2000 within catchment
PctFire2001Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2001 within catchment
PctFire2002Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2002 within catchment
PctFire2003Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2003 within catchment
PctFire2004Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2004 within catchment
PctFire2005Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2005 within catchment
PctFire2006Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2006 within catchment
PctFire2007Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2007 within catchment
PctFire2008Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2008 within catchment
PctFire2009Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2009 within catchment
PctFire2010Ws	USEPA StreamCat	% Forest loss to fire (fire perimeter) for 2010 within catchment

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Predictor Variables	Source	Description
PctGrs2011Ws	USEPA StreamCat	% of catchment area classified as grassland/herbaceous land cover (NLCD 2011)
PctMxFst2011Ws	USEPA StreamCat	% of catchment area classified as grassland/herbaceous land cover (NLCD 2011)
PctShrb2011Ws	USEPA StreamCat	% of catchment area classified as grassland/herbaceous land cover (NLCD 2011)
PerAvgSlope	USGS National Map	30-meter resolution digital elevation acquired from the USGS National Map was used to calculate the percent average slope in each watershed
PermWs	USEPA StreamCat	Mean permeability (cm/hour) of soils (STATSGO) within watershed
Precip8110Ws	USEPA StreamCat	Mean permeability (cm/hour) of soils (STATSGO) within watershed
PrevAvgPrecip-Km	PRISM	Average watershed precipitation from PRISM datasets at 30-meter resolution
RckDepWs	USEPA StreamCat	Mean depth (cm) to bedrock of soils (STATSGO) within watershed
RunoffWs	USEPA StreamCat	Mean runoff (mm) within watershed
SandWs	USEPA StreamCat	Mean % sand content of soils (STATSGO) within watershed
SH1	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Low load dry climate shrub, woody shrubs and shrub litter, fuelbed depth about 1 foot, may be some grass, spread rate and flame low
SH2	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Moderate load dry climate shrub, woody shrubs and shrub litter, fuelbed depth about 1 foot, no grass, spread rate and flame low
SH5	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: High load, humid climate grass-shrub combined, heavy load with depth greater than 2 feet, spread rate and flame very high
SH7	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Very high load, dry climate shrub, woody shrubs and shrub litter, very heavy shrub load, depth 4-6 feet, spread rate somewhat lower than SH6 and flame very high
TBurnSqKm	BAER Soil Burn	% burned in watershed, calculated by summing the percentage of low, moderate and highly burned percent area.
TL1	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Low load compact conifer litter, compact forest litter, light to moderate load, 1-2 inches deep, may represent a recent burn, spread rate and flame low
TL2	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Low load broadleaf litter, broadleaf, hardwood litter, spread rate and flame low

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Predictor Variables	Source	Description
TL3	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Moderate load conifer litter, moderate load conifer litter, light load of coarse fuels, spread rate and flame low
TL4	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Small downed logs moderate load of fine litter and coarse fuels, small diameter downed logs, spread rate and flame low
TL6	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Moderate load broadleaf litter, spread rate and flame moderate
TL7	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Large downed logs, heavy load forest litter, larger diameter downed logs, spread rate and flame low
TL8	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Long needle litter, moderate load long needle pine litter, may have small amounts of herbaceous fuel, spread rate moderate and flame low
TL9	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Very high load broadleaf litter, may be heavy needle drape, spread rate and flame moderate
Tmean8110Ws	USEPA StreamCat	PRISM climate data - 30-year normal mean temperature (°C): Annual period: 1981-2010 within the watershed
TU1	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Low load dry climate timber grass shrub, low load of grass and/or shrub with litter, spread rate and flame low
TU2	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Moderate load, humid climate timber-shrub, moderate litter load with some shrub, spread rate moderate and flame low
TU5	Landfire (40 Scott and Burgan Fire Behavior Fuel Models)	Vegetation: Very high load, dry climate shrub, heavy forest litter with shrub or small tree understory, spread rate and flame moderate
ValleySlope	USGS National Map	Valley Slope calculated from an euclidean distance raster from top to bottom of a watershed and slope raster created from 30-meter DEM
WsAreaSqKm	USEPA StreamCat	Watershed area (square km) at NHDPlus V2 stream segment outlet, i.e., at the most downstream location of the vector line segment
WtDepWs	USEPA StreamCat	Mean seasonal water table depth (cm) of soils (STATSGO) within watershed
Year	CEDEN or SWAMP Survey	Year the CEDEN or SWAMP survey was completed
YrSinceLastFire	Landfire (Fire Regimes)	Year since last wildfire within watershed using Landfire Fire Regime Groups