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Turbidity Responses from Timber Harvesting, Wildfire, and Post-Fire Logging in the Battle Creek Watershed, Northern California

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Abstract

The Battle Creek wa tershed in northern California was historically important for its Chinook salmon populations, now at remnant levels due to land and water uses. Privately owned portions of the watershed are managed primarily for timber production, which has intensified since 1998, when clearcutting became widespread. Turbidity has been monitored by citizen volunteers at 13 locations in the watershed. Approximately 2000 grab samples were collected in the 5-year analysis period as harvesting progressed, a severe wildfire burned 11,200 ha, and most of the burned area was salvage logged. The data reveal strong associations of turbidity with the proportion of area harvested in watersheds draining to the measurement sites. Turbidity increased significantly over the measurement period in 10 watersheds and decreased at one. Some of these increases may be due to the influence of wildfire, logging roads and haul roads. However, turbidity continued trending upwards in six burned watersheds that were logged after the fire, while decreasing or remaining the same in two that escaped the fire and post-fire logging. Unusually high turbidity measurements (more than seven times the average value for a given flow condition) were very rare (0.0% of measurements) before the fire but began to appear in the first year after the fire (5.0% of measurements) and were most frequent (11.6% of measurements) in the first 9 months after salvage logging. Results suggest that harvesting contributes to road erosion and that current management practices do not fully protect water quality.

Keywords Turbidity · Water quality · Timber harvest · Cumulative watershed effects · Wildfire · Salvage logging

Introduction

Elevated sediment concentration has been identified as a widespread water quality problem in surface waters of the United States (USEPA 2000). Wildfire and timber harvesting activities often affect sediment concentrations and associated turbidity by increasing erosion and sediment delivery to streams and rivers. This study uses multi-year citizen monitoring data collected in several subwatersheds of Battle Creek in northern California to examine the relative impacts on turbidity from recent logging, wildfire, and post-fire salvage timber harvest.

Wildfire is an ecologically important disturbance that often transiently elevates soil erosion and sediment delivery to streams, primarily due to the loss of soil cover and increased runoff (Robichaud et al. 2010). The duration and magnitude of these effects generally increase with increasing fire severity and areal extent (Wondzell and King 2003). Low-severity fire usually has nominal and fleeting erosional impacts (e.g., Surfleet et al. 2014), while higher-severity fire can greatly increase erosion and sediment delivery (e.g., Rhoades et al. 2011). However, such increases seldom persist for more than three years in the absence of subsequent anthropogenic disturbances, due to post-fire recovery of soil properties and cover via revegetation and the recruitment of dead needles and wood (Pannkuk and Robichaud 2003),

Wildfire sometimes causes hydrophobic soils, which can vastly increase runoff and sediment delivery in subsequent storms (Moody and Martin 2001; Shakesby and Doerr 2006). However, major post-fire runoff and sedimentation events are relatively rare and geographically restricted because they are contingent on relatively high-intensity

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storms affecting hydrophobic soils while the soils exhibit water repellency. Fire does not always cause soil hydrophobicity. Soil wetting reduces or eliminates fire-induced hydrophobicity (MacDonald and Huffman 2004), causing it to decline, sometimes rapidly, after fire (Wondzell and King 2003). Thus, major post-fire erosional and runoff events are typically triggered by the occurrence of relatively high intensity storms when transiently hydrophobic soils are relatively dry. The confluence of these conditions is relatively rare in areas dominated by snowmelt or frequent low intensity rain, such as the U.S. Pacific Northwest, and is more likely in areas with dry summers punctuated with thunderstorms, such as the southwestern U.S. (Wondzell and King 2003).

Earlier assessments (Kattelmann 1996; Beschta et al. 2004; Karr et al. 2004) noted that post-fire logging likely increases the magnitude and duration of erosion and sediment delivery after fires, delaying watershed and aquatic recovery. Research has confirmed that post-fire salvage logging impedes revegetation, compacts soils, and elevates runoff and soil erosion, adding to fire's erosional impacts and slowing post-fire aquatic recovery in the western U.S. (Donato et al. 2006; Wagenbrenner et al. 2015, 2016) and Australia (Smith et al. 2012).

While some wildfires may have greater immediate impacts than logging on sediment production (e.g. Silins et al. 2009), logging activities have more persistent soil impacts than fire (Beschta et al. 2004). Unlike transient fire effects on soils, complete recovery of soil properties is unlikely on highly compacted landings and roads, even with remediation (Beschta et al. 2004; Foltz et al. 2007).

With or without fire, logging activities such as ground-based yarding, landing, and road use and construction, commonly damage soils and increase erosion and sediment delivery, degrading water quality and aquatic habitats (Gucinski et al. 2001; NRC 2008; Croke and Hairsine 2006). Road traffic for log haul increases erosion and subsequent delivery of fine sediment to streams (Reid et al. 1981; Reid 1998). Winter operations on wet roads can accelerate rill erosion and cause rutting (Foltz and Burroughs 1990; Reid 1998). Geomorphology and geology strongly influence the degree of these sediment impacts from timber harvest on streams (Bywater-Reyes et al. 2017), and adverse effects can potentially be reduced via management of runoff pathways (Croke and Hairsine 2006).

Wildfire and logging both reduce evapotranspiration and canopy interception (Reid and Lewis 2009; Cafferata and Reid 2013; Link et al. 2004), contributing to increased runoff and streamflow (LaMarche and Lettenmaier 2001; Wondzell and King 2003). Increased streamflow typically increases bank and bed erosion (Dunne et al. 2001), which are significant erosional processes in small forested watersheds (Hassan et al. 2005).

Best management practices (BMPs) for logging operations can reduce sediment-related impacts on aquatic systems. However, their cumulative effectiveness remains controversial, because BMPs do not always eliminate impacts and data on their cumulative effectiveness at watershed scales are limited (Ziemer and Lisle 1993; Rhodes et al. 1994). Hillslope-scale studies (Rashin et al. 2006; Litschert and MacDonald 2009) have concluded that while BMPs did not eliminate erosion from logging activities, they prevented much of the generated sediment from reaching streams. However, watershed-scale studies of turbidity and sedimentation have indicated that BMPs do not prevent significant sediment-related impacts from logging activities (Espinosa et al. 1997; Klein et al. 2012). Site factors, such as slope, rainfall, and stream proximity can significantly limit BMP effectiveness (Great Lakes Environmental Center 2008). Existing BMPs for post-fire logging do not appear adequate to completely prevent increased soil erosion and runoff in some settings (Wagenbrenner et al. 2016).

Turbidity provides an index of suspended sediment transport (Lewis 1996), thus can be an indication of the efficacy of best management practices (BMPs) aimed at preventing sedimentation. Sediment concentrations associated with high turbidity can result in deposition, elevating fine sediment levels in substrate, lowering pool volumes (Lisle and Hilton 1992; Buffington and Montgomery 1999; Cover et al. 2008), and reducing salmonid survival and production in several ways (USFS et al. 1993; Suttle et al. 2004).

Study Area

The Battle Creek watershed in northern California drains approximately 960 km^2 on the west side of Lassen National Park. Watershed elevation ranges from 100 m at the Sacramento River confluence to 3187 m at Mt. Lassen Peak. The watershed's annual precipitation averages 122 cm year^{-1} (Myers 2012), ranging from <76 cm year^{-1} falling primarily as rain at lower elevations, to >317 cm year^{-1} at higher elevations, falling primarily as snow. On average, 93% of the precipitation occurs from October to May. Major tributaries in the watershed include North Fork Battle Creek (NFB), Bailey Creek, Rock Creek, Digger Creek, and South Fork Battle Creek (SFB).

Watershed slopes are generally less than 15% (Myers 2012), with steeper areas (15–40%) in the South Fork and at higher elevations. Many of the creeks lie in steep-sided canyons that are 15–30 m in depth. Geology is primarily volcanic, with andesitic, basaltic, rhyolitic, and dacitic soils and pockets of glacial and alluvial soils (USDA 1967, 1974). The porous bedrock gives rise to numerous springs throughout the area. Soils have high infiltration rates and turbidity is low under natural conditions because streamflow is generated primarily by sediment-poor groundwater.

In the monitored subwatersheds, 47 km^2 are in Lassen National Park, 215 km^2 are in Lassen National Forest, and 495 km^2 are privately owned. Logging and recreation are primary land uses in the National Forest. Timber production is the dominant activity on private lands. Residential and agricultural use affects a relatively small part of the land base (Supplemental material: Fig. S1).

Logging in Battle Creek began in the late 19th century. After decades of little disturbance in the mid to late 20th century, logging intensified again beginning in 1998, when clearcutting in ~8-ha tracts became the dominant silvicultural method. Between 1998 and 2012, ~8500 ha in the watershed were designated for harvest under Timber Harvesting Plans (THPs). The 2012 Ponderosa Fire burned 11,200 ha in the watershed. Most of the timber that had not already been logged in burned areas was harvested within a year after the fire. The fire footprint and a checkerboard pattern of clearcuts are the most conspicuous landscape features on the watershed's privately owned industrial timberland in the 2014 satellite image (Supplemental Materials: Fig. S2).

There are numerous major water diversions in the watershed, primarily for hydroelectric dams and powerhouses. Water diversion reports from 2003 to 2011 indicate that an average of 1.3×10^8 m^3 of water was diverted annually from the North Fork to the South Fork above site SFB, enhancing the mean annual flow at SFB by 87%. Thus, water quality measurements at SFB probably reflect, to a significant extent, conditions in the NFB watershed. Of the total diverted flow, 9.3×10^7 m^3 are withdrawn upstream of site NFB, about 52% of the annual flow at that site. (Annual flows at NFB and SFB are estimated, based on watershed areas relative to the U.S. Geological Survey (USGS) gage at Coleman National Fish Hatchery, located 17 km downstream from the confluence of the North and South Forks). Because water quality at SFB is strongly influenced by diversions from the North Fork, SFB was omitted from analyses relating turbidity to timber harvesting, but was included in trend analyses.

Battle Creek provides habitat for steelhead trout (*Oncorhynchus mykiss*) and winter-run and spring-run Chinook salmon (*Oncorhynchus tshawytscha*). Historically, the size and diversity of the watershed's Chinook salmon populations were significant, but these populations are at remnant levels due to the cumulative impacts of land and water uses (Yoshiyama et al. 1998; Kier Associates 2009), including migration barriers and water diversions for hydroelectric power. Winter-run Chinook are listed as endangered and Spring-run Chinook are listed as threatened under federal and state Endangered Species Acts. The Battle Creek Salmon and Steelhead Restoration Project currently aims to restore about 77 km of habitat through modification of hydroelectric project facilities, operations, and management.

Methods

Measurement Sites

All of the monitoring sites drain industrial timberlands and include upstream and downstream locations on four Battle Creek tributaries, as well as one site each on the North and South Forks of Battle Creek (Table 1; Fig. 1). Drainage areas in Table 1 are based upon surface topography but may not be proportional to flows due to numerous water diversions and porous bedrock, which likely allows some portion

Table 1 Sampling sites and characteristics

Site ID	Name	Elev (m)	Drainage area (ha)	Percent logged	Watershed notes
BCT	Bailey Creek upper	1216	4182	13.1	Upstream of burned area, drains mostly federal lands
BCP	Bailey Cr lower	701	8333	33.9	Downstream of a major spring
CCC	Canyon Cr upper	1146	130	40.2	An intermittent tributary to Canyon Creek
CCSP	Canyon Cr spring	1146	0	0.0	The source of Canyon Creek: a spring with no surface catchment
CC2	Canyon Cr middle	1064	421	80.7	100% burned and salvaged below CCC
CC	Canyon Cr lower	963	757	89.2	100% burned and salvaged below CCC
RC	Rock Cr upper	942	4850	40.4	Lower third was heavily burned
RCP	Rock Cr lower	710	5982	47.3	Includes CC and RC drainages
DC	Digger Cr upper	1049	5474	15.8	Upstream of fire and salvage-logged area
FMC	Digger Cr trib	939	<4	100.0	An intermittent tributary to Digger Creek
DCH	Digger Cr lower	786	9089	23.7	Just downstream of fire boundary
NFB	North Fork Battle	585	36,910	28.2	Includes Bailey and Rock Creek but not Digger
SFB	South Fork Battle	287	30,948	12.7	Last to be harvested, receives NF diversions

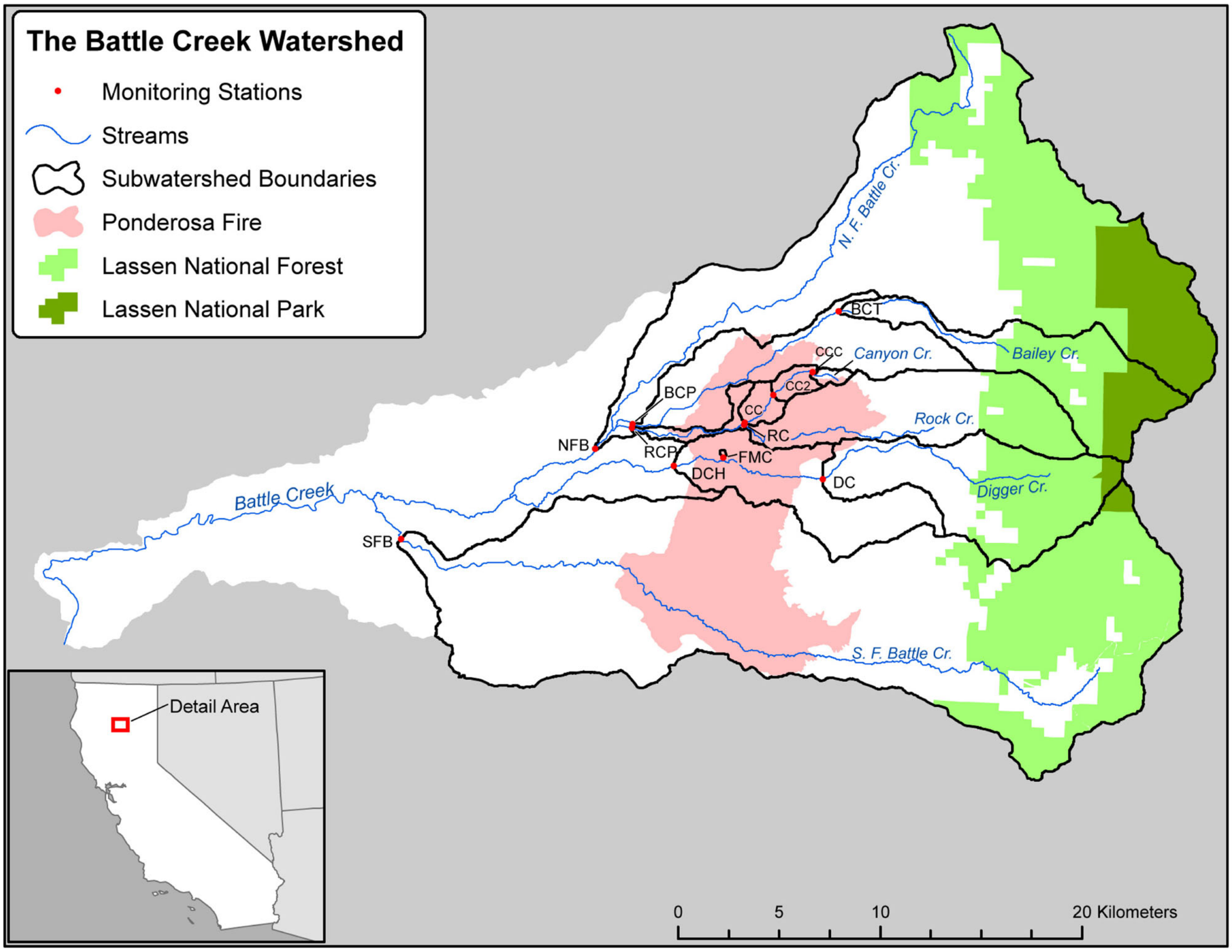

Fig. 1 Battle Creek monitoring sites, subwatersheds, and Ponderosa Fire footprint

of infiltrated water to emerge as spring water in different surface drainage basins.

Data Collection

Battle Creek Alliance (BCA) volunteers, trained by scientists from the California Department of Fish and Wildlife, sampled and measured 2003 turbidity samples between Dec 30, 2009 and March 23, 2015, using a Hanna Instruments HI 98703 portable turbidimeter that was calibrated monthly. The manufacturer indicates that the HI 98703 meets the USEPA requirements for wastewater and drinking water turbidity measurements. It is designed for accuracy and sensitivity at low turbidity, with a measurement range of 0 to 1000 NTU. Measured turbidity exceeded the upper limit 8 times, and in those instances was recorded as 1000.

BCA collected data throughout the watershed 37–49 days per year, more frequently than typical USGS monitoring programs. All sites were usually sampled in a single day, at 7–12 day intervals. Additional samples were collected after storms, often on consecutive days or every other day. Storm flows representing the highest 5% of annual flows (~18 days/year) accounted for 12.5% of samples collected. Turbidity is most sensitive to the finest, most easily suspended particles and these are small well-mixed creeks, so it was not difficult to collect representative grab samples at stream riffles. The vial was rinsed in streamwater before extracting each turbidity sample. Due to logistics, very few samples were collected during the rising limb of storm hydrographs when turbidity would be highest if sediment and turbidity peak before discharge, as is common in fluvial systems.

The areas logged in subwatersheds were estimated from several sources. Drainage boundaries and areas for each sampling site were GIS-derived from 10-m DEMs. The proportion harvested in each drainage was estimated from Google Earth images, available at irregular intervals. When new cut blocks appeared on the satellite images, the number of blocks in each THP was counted by drainage, multiplied

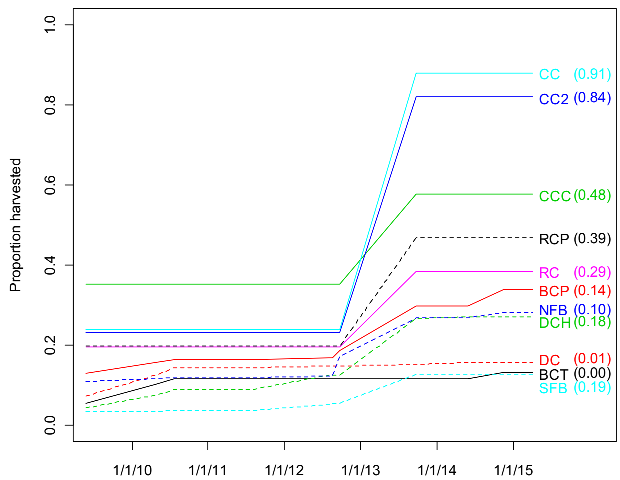

Fig. 2 Progression of harvesting in Battle Creek drainages. Numbers in parentheses are the proportions of each drainage that burned in the Ponderosa Fire. Post-fire salvage logging began in Sep 2012

by the average size cut block for that THP, and summed to determine the newly harvested area in each drainage. The procedure assumes that harvesting for roads and other silvicultural methods was conducted concurrently in proportion to the clearcutting.

The area logged in subwatersheds after the 2012 Ponderosa Fire (Figs. 1, 2) was calculated as the timberland within the fire boundary minus (1) areas which had been previously harvested and (2) specific areas identified from Google Earth images as having not been salvage logged. Using this approach, the logged proportions of each watershed were estimated at the dates of each Google Earth image, including immediately before and after the fire. Inspection reports from the California Department of Forestry and Fire Protection (CALFIRE) indicate that post-fire logging was completed within one year after the fire.

The proportion harvested was estimated at the time of each turbidity measurement by interpolating linearly between dates (Fig. 2). Winter operations were common during the monitoring period and CALFIRE inspection reports confirm that logging occurred during the winter following the Ponderosa fire, so the assumption of uniform rates of harvest is a plausible approximation. Sites CC and CC2 had the highest proportions of their drainage areas logged. Site FMC was logged after the Ponderosa fire but only a few measurements were taken because it has been dry after alteration of the channel by equipment and subsequent drought. For sites other than FMC and those in Canyon Creek, drainage areas include unlogged forestland upstream in Lassen National Park and Lassen National Forest. Site CCSP was affected by post-fire logging, but it was omitted from Fig. 2 because it is a spring with no surface catchment; its watershed area and proportion harvested are coded as zero.

Basin characteristics were extracted using Streamstats (USGS 2012) and the TIGER/Line database (U.S. Census Bureau 2014), including elevation range, mean elevation, percent of basin above 1829 m (6000 ft), relief ratios (elevation range divided by basin perimeter or longest flow path), mean annual precipitation, and mean basin slope. The TIGER/Line shapefiles were downloaded and edited to remove redundant road segments. Ownership was determined from the Environmental and Geospatial Technologies ENPLAN parcel viewer (http://pv.enplan.com), where it was not available from TIGER data. Roads were classified by ownership, and densities determined for (1) all roads, (2) near-stream roads (within 100 m of streams), and (3) very near-stream roads (within 30.5 m of streams) based on the USGS National Hydrologic Dataset (http://nhd.usgs.gov).

Current Logging Practices

Logging practices within the watershed are regulated by California's Forest Practice Rules, Fish and Game Code, and water quality control law. The Rules require a THP for each proposed logging operation. The THP is intended to evaluate potential direct and cumulative impacts that might occur as a result of the logging plan and provides measures to reduce these impacts to levels that the THP assumes are insignificant.

Even-aged management (clearcutting and shelterwood) is the most common logging method in the watershed, with occasional commercial thinning, group selection, or clearing for fuel breaks and roads. Most logging uses ground-based equipment to fell and drag logs to landings where logs are loaded onto trucks for transport. Post-fire logging typically removed all dead and damaged trees measuring ≥30 cm in diameter at 1.2 m height, but may also have included removal of most submerchantable biomass. Slopes less than approximately 35% were treated by contour ripping (subsoiling) to a depth of 50 cm after salvage logging, with the aim of reducing runoff and flow concentration (USFS 2008). Within the private timberlands in the fire perimeter, approximately 95% of the NFB drainage and 79% of the SFB drainage have slopes less than 35%. After salvage logging, pre-emergent herbicides are commonly applied to prevent non-conifer regrowth, except in some riparian areas.

Statistical Methods

Multiple Regression Model

Discharge data were unavailable at individual sampling sites, so a regression model was developed to predict daily

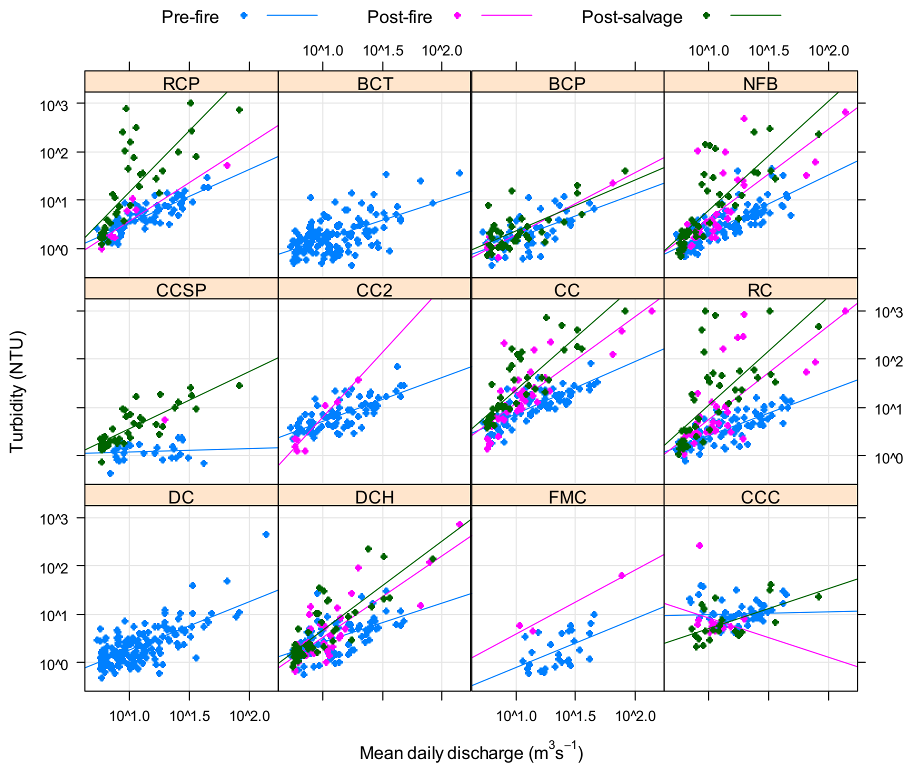

Fig. 3 Relationships between turbidity and mean daily discharge at Coleman Fish Hatchery for the pre-fire, post-fire, and post-salvage periods

turbidity at each site from mean daily discharge (MDQ) at the Coleman Hatchery gaging station. Instantaneous discharge was not used in the regression model because, for several reasons, the Coleman hydrographs are unlikely to be well-synchronized with those at the sampling sites. However, there were positive relationships between the Coleman MDQ and turbidity (T) at all sampling sites (Fig. 3). The relative daily change in MDQ ($\Delta\text{MDQ} = MDQ/MDQ1$), in which $MDQ1$ is the previous day's mean daily discharge, was included in the regression model to distinguish receding from rising limbs of hydrographs. Precipitation intensity in the 1, 2, and 3-h periods prior to the measurement was also tested, and the square root of the 3-h intensity (denoted PPT3) was found to be the best predictor.

$$\log(T) = \beta_{0,i} + \beta_{1,i}\log(\text{MDQ}) - \beta_2\log(\Delta\text{MDQ}) + \beta_3\text{PPT3}^{0.5} \quad (1)$$

All sites were combined in the model, but separate intercepts $\beta_{0,i}$ and coefficients $\beta_{1,i}$ for MDQ were estimated for each sampling site i.

Trends in Multiple Regression Residuals

Trends were visualized at each site by plotting the residuals from model (1). Trends in turbidity were tested for the full monitoring period, as well as the separate periods before and after the fire using the "adjusted variable" Mann-Kendall test (Alley 1988) recommended by Helsel and Hirsch (2002). This non-parametric procedure does not require normally distributed residuals and equal variance under all conditions. Alley's test is a Mann-Kendall test on the partial regression plot of log(T) versus time. For the partial regression plot, log(T) and time are both regressed on the same set of predictors: log(MDQ), log(ΔMDQ), and $\text{PPT3}^{0.5}$. The two sets of residuals are plotted against one another and tested for monotonic trend using the usual Mann-Kendall test. Since there were 13 sites to be tested, the family wise Type I error rate was kept to 0.05 using the Bonferroni correction, i.e., the critical p-value was set to $\alpha = 0.05/13 = 0.0038$ for each test.

Finally, Alley's test was repeated using proportion harvested in place of time. This provides a more reliable test of harvesting than a standard t-test of a regression coefficient because of the violated regression assumptions. It also helps determine whether temporal trends may actually be related to logging levels.

Frequency of High Multiple Regression Outliers

For salvage-logged watersheds, the frequency of residuals greater than 2 (indicating a value more than $e^2 = 7.4$ times the prediction from model (1)) was compared for the pre-fire period and subsequent periods using chi-square contingency tests. This permitted evaluation of both fire effects and post-fire logging effects. Salvage logging was ongoing in the first year after the fire (from Sep 2012 to Sep 2013), which we have designated as the "post-fire" period. Although the post-fire period included some post-fire logging, the average level of disturbance is less than during the subsequent "post-salvage" period. Post-fire logging was assumed to have been completed by Sep 21, 2013 and this data set extends to Mar 23, 2015. The post-salvage period was divided into two 9-month periods (at Jun 21, 2014), each including one wet season, for evaluation of turbidity impacts.

Associations of Site Differences with Harvesting

A second regression model that does not distinguish among sites was fitted with the same predictors as Eq. (1):

$$\log(T) = \beta_o + \beta_1 \log(\mathrm{MDQ}) - \beta_2 \log(\Delta\mathrm{MDQ}) - \beta_3 \mathrm{PPT3}^{0.5} \tag{2}$$

Differences among sites are reflected in the residuals. The median turbidity and mean residual for each site, and the 90th percentiles of both variables, were tested for association with proportion harvested, averaged over the sampling dates at each site. Statistical significance was tested using both the Pearson correlation coefficient and Kendall's tau, a non-parametric alternative.

Partial Correlation Analysis

Bivariate analyses relating turbidity to proportion of area harvested are potentially misleading if there are variables correlated with area harvested that contribute to variability in turbidity. Many of the basin characteristics (including roads, harvesting, occurrence of fire, and topographic variables) are correlated with each other, so a partial correlation analysis was undertaken using the R package *ggm* (Marchetti and Drton 2010). The partial correlation measures how well two variables are correlated after accounting for the information in one or more possible confounding variables. It would indicate, for example, what proportion of the variation in variable y can be explained by predictor x_2 beyond that already explained by predictor x_1. Sites SFB, CCSP, and FMC were omitted from the partial correlation analyses for reasons already discussed and because the very small area of FMC enormously magnified its road density.

Results

Turbidity Levels and Fitted Regression

The sites with the highest median turbidity are in Canyon Creek (CC, CCC, and CC2), followed by the Rock Creek sites (RCP and RC) (Fig. S4). These are followed by the North Fork, South Fork, and Digger Creek sites, all of which integrate upstream impacts from wildfire and clear-cutting. Turbidity appears to have increased after fire and/or post-fire logging at NFB, CC, CCSP, RC, RCP, and DCH (Fig. 3). At all those sites, turbidity after post-fire logging is, on average, higher than after fire alone. The remaining sites either did not burn (BCT, DC), had a small fraction that burned (BCP), were lightly burned and minimally salvaged (CCC), or had very few post-fire measurements (CC2, FMC). The differences in Fig. 3 were not statistically tested, as the multivariate model (1) provided a stronger fit to the data ($R^2 = 0.56$).

The fitted multivariate model (2) explained 31% of the variability in log(T) among turbidity samples:

$$\log(T) = -5.28 + 1.11 \log(\mathrm{MDQ}) + 0.169 \log(\Delta\mathrm{MDQ}) + 1.07\mathrm{PPT3}^{0.5} \tag{3}$$

Adding the proportion harvested to this model explains an additional 21% of the variability in log(T). Its coefficient (3.17) implies ~5-fold increase in turbidity from harvesting 50% of a watershed and a 24-fold increase from a 100% harvested watershed. However, the most harvested watersheds are also the ones that were most extensively burned.

Multiple Regression Outlier Residuals

The variability implied by the model (3) residuals (Fig. 4) is large. Because the response variable is the natural logarithm of turbidity, a value of 4 on the residuals axis indicates that the turbidity was $e^4 = 55$ times that predicted by the regression (i.e., 55 times the average turbidity expected during the monitoring period for those flow conditions). Among all sites, there are 65 residuals greater than 2 (7.4 times predicted), and all but one occurred after the 2012 Ponderosa fire; 52 of the 65 were measured in 2014, after salvage logging had been completed. Residuals greater than 2 occurred most frequently at RC (14 occurrences), RCP (12), NFB (12), CC (10), and DCH (7). Unburned watershed BCT had no occurrences after the fire and DC, had only one. CCSP had a dramatic increase in turbidity: 48 of 49 residuals greater than 0 occurred after salvage logging was completed. The majority of post-fire turbidity values at CCSP exceeded the *maximum* of 2.3 NTU measured pre-fire. Ground disturbance from post-fire logging occurred just above this monitored spring. However, only one measurement was made after the fire and before salvage logging, so the two effects cannot be statistically distinguished at CCSP.

A contingency table was made using all fire-affected sites (including SFB), to help separate fire effects from

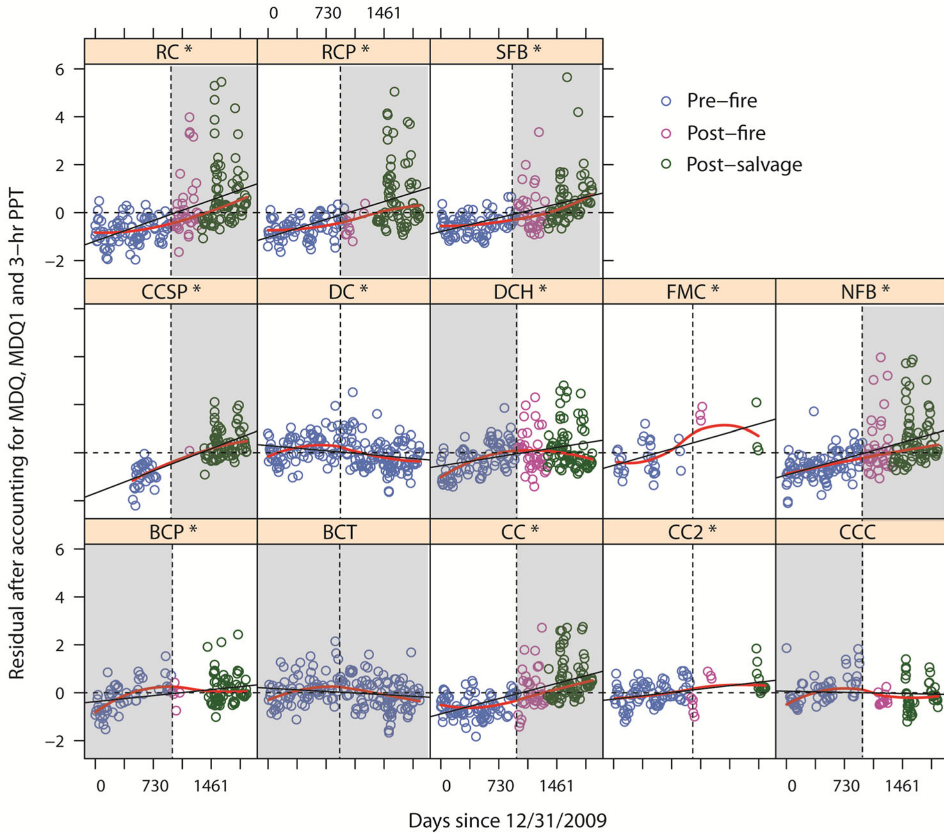

Fig. 4 Temporal trends in regression residuals. Regression response is the natural logarithm of turbidity, so vertical axis is in log units to the base $e = 2.7183$. Predictor variables in the regression are MDQ, ΔMDQ (the one-day relative change MDQ/MDQ1), and PPT3. A separate MDQ coefficient was estimated for each site. Asterisk (*) indicates a significant trend over the entire period. Shading indicates a significant trend over either the pre-fire period or the combined post-fire and post-salvage periods. Rejection level for adjusted Mann-Kendall test was set at $p < 0.0038$, applying Bonferroni's correction for 13 simultaneous tests

post-fire logging effects (Table 2). The ratio of unusually high residuals (greater than 2) to other residuals increased from none pre-fire, to 5.0% in the year after the fire, to 11.6% in months 1–9 after post-fire logging completion, then declined to 6.0% in months 10–18 after post-fire logging. The probability of these ratios changing that much by chance is negligible ($p < 10^{-6}$). We tested each of the five sites listed above that had 7 or more residuals greater than 2 during the measurement period. All tests were highly significant ($p < 0.01$). These results suggest strongly that turbidity was elevated much more frequently by the combination of fire and salvage logging than by fire alone, and that the greatest impacts from post-fire logging were during the first winter after logging. The maximum turbidity measured at any of the monitoring sites was 81 NTU in almost 3 years of monitoring before the Ponderosa Fire. Values from 81 to 1000 NTU were measured 22 times in the 12 months after fire, 39 times in the first 9 months after post-fire logging and 20 times in the second 9 months after post-fire logging.

Multiple Regression Residual Trends

Overall residual trends (Fig. 4) were statistically significant for all monitored sites except CCC and BCT. Turbidity increased at 10 measurement sites over the analysis period. Sites DC and BCT, which were largely unaffected by fire and have been relatively undisturbed since the summer of 2010, exhibit a gradual decline in turbidity from 2013 to 2015. Site CCC apparently also declined slightly, but as with BCT, the decline was not significant. The satellite images indicate very little of the drainage area of CCC had burned, with most of the post-fire logging far away from the creek. Measurements were discontinued at FMC because the channel was altered by heavy logging equipment and now rarely conveys any flow. Until 2015, only three post-fire turbidity measurements were made at FMC, but those do suggest a fire effect (Figs. 3, 4).

During the pre-fire period, there were no significant declines in the turbidity residuals at any site, while turbidity residuals increased significantly at sites DCH, CCC, BCT, and BCP (Fig. 4). The pre-fire increases occurred during periods of harvesting at DCH, BCT, and BCP, but not at CCC. Logging in the Canyon and Rock Creek sub-watersheds last occurred before May 2009 and was not resumed until after the fire. The smaller number of significant positive trends in the pre-fire data may be partly due to the smaller sample size inherent in the shorter period, but it may also be related to a lull in harvesting in Rock Creek and Canyon Creek.

Table 2 Contingency tests comparing the frequencies of regression residuals greater than 2 (indicating turbidity more than 7.4 times the prediction based on model 3) before the fire, and in each post-fire period

Site		Pre-fire (WY2010-WY2012)	Post-fire (WY2013)	1–9 months after post-fire logging	10–18 months after post-fire logging	Significance level (p)
All but DC and BCT	Residuals > 2	0	11	36	16	
	Residuals ≤ 2	756	219	310	265	
	Ratio	0.0000	0.0502	0.1161	0.0604	0.0000
NFB	Residuals > 2	0	3	9	1	
	Residuals ≤ 2	97	38	34	31	
	Ratio	0.0000	0.0789	0.2647	0.0323	0.0001
RC	Residuals > 2	0	4	7	3	
	Residuals ≤ 2	90	36	36	29	
	Ratio	0.0000	0.1111	0.1944	0.1034	0.0044
CC	Residuals > 2	0	1	7	2	
	Residuals ≤ 2	87	38	36	30	
	Ratio	0.0000	0.0263	0.1944	0.0667	0.0010
RCP	Residuals > 2	0	0	7	5	
	Residuals ≤ 2	77	9	32	26	
	Ratio	0.0000	0.0000	0.2187	0.1923	0.0029
DCH	Residuals > 2	0	1	5	1	
	Residuals ≤ 2	84	36	36	30	
	Ratio	0.0000	0.0278	0.1389	0.0333	0.0067

To avoid assuming a chi-squared approximate distribution for the test statistic, statistical significance was computed by Monte Carlo simulation (10^6 permutations). Significance levels are for the 2×4 contingency tables for each site

During the post-fire period, six sites with post-fire logging exhibited statistically significant turbidity increases, while the unburned site BCT declined significantly. At all six sites that increased, there were also significant positive associations ($p < 0.0001$) between turbidity and harvest level (Supplemental Materials: Fig. S5).

In the one-year post-fire period, the mean regression residual increased at all sites (except CCC) draining watersheds with burned areas (Table 3). The mean post-fire change in turbidity in these watersheds (including CCC) was 66%. At the two sites above the fire, the mean change during this period was small (−14% at DC and 2.5% at BCT).

In the combined post-salvage periods, the mean regression residual increased at all sites draining burned areas. The mean post-salvage change in turbidity in these watersheds was 63% relative to the post-fire period. At the two sites upstream of the fire, the mean change during the post-salvage period was −29% at DC and −35% at BCT. The Spearman correlation of 0.78 between mean post-salvage change and proportion of watershed salvage-logged is statistically significant ($p = 0.012$). (Sites FMC and CCSP are excluded from the above statistics because of their very small sample sizes (3 and 1) during the one-year post-fire period).

Tests of Association of Turbidity with Proportion of Subwatershed Area Harvested

The median and 90th percentiles of sample turbidity values are both strongly associated with mean proportion of subwatershed area harvested, for both the entire study period and the pre-fire period. Similar results accrue with the mean and 90th percentiles of residuals from model (3) substituted for the sample turbidities (Table 4). In the full study period, harvesting is confounded with co-occurrence of the Ponderosa Fire, but the associations are even stronger in the pre-fire period (Table 4; Fig. 5). The three Canyon Creek sites (CC, CC2, and CCC) exhibit the highest pre-fire residual means and 90th percentiles, followed by the Rock Creek sites (RC, RCP) and Lower Digger Creek (DCH).

Partial Correlation Analysis of Predictor Variables and Turbidity Metrics

The associations in rows 1, 2, 5, and 6 of Table 4 are likely at least partly due to the effects of the 2012 Ponderosa fire. An examination of partial correlations (Supplemental Materials: Fig. S8) revealed that area harvested appears to be more important than fire, but due to the small number of sites, most of the partial correlations are not statistically

Table 3 Percent change in turbidity, accounting for hydrologic conditions, based on residual means from model (1) in the pre-fire, post-fire and combined post-salvage periods

Site	Percent post-fire change	Percent post-salvage change	Sample size post-fire (12 months)	Sample size post-salvage (18 months)
DC (unburned)	−14.2	−28.9	85	36
DCH	43.2	19.4	84	35
FMC	540.6	−54.4	28	3
CCC (lightly burned)	−34.2	18.7	53	12
CCSP	181.2	34.0	29	1
CC2	−1.7	68.5	78	8
CC	89.5	67.4	87	37
RC	167.1	67.2	90	38
RCP	12.0	245.6	77	9
BCT (unburned)	2.5	−34.8	81	30
BCP	11.2	22.5	51	5
NFB	119.8	35.7	97	38
Mean for watersheds affected by the fire, excluding FMC and CCSP	66.5	63.1		
Mean for unburned watersheds, DC and BCT	−5.8	−31.87		

Post-salvage changes are relative to the post-fire period. Except where noted, all sites included burned areas

Table 4 Associations of sampled turbidity and regression residuals with mean proportion harvested in each subwatershed

	Harvest variable	Turbidity variable	Pearson correlation	*p*-value	Kendall's tau	*p*-value
1	Mean proportion harvested	Median sample turbidity	0.894	0.0001	0.788	0.0001
2	Mean proportion harvested	90th percentile sample turbidity	0.732	0.0068	0.576	0.0088
3	Mean pre-fire proportion harvested	Median sample turbidity	0.792	0.0022	0.718	0.0012
4	Mean pre-fire proportion harvested	90th percentile sample turbidity	0.866	0.0027	0.809	0.0003
5	Mean proportion harvested	Mean regression residual	0.816	0.0012	0.758	0.0002
6	Mean proportion harvested	90th p-tile regression residual	0.714	0.0090	0.636	0.0032
7	Mean pre-fire proportion harvested	Mean pre-fire residual	0.909	0.0000	0.748	0.0008
8	Mean pre-fire proportion harvested	90th p-tile pre-fire residual	0.909	0.0000	0.687	0.0020

Proportion harvested is averaged over all sampling dates (rows 1, 2, 5, and 6) or dates prior to the Ponderosa Fire (rows 3, 4, 7, and 8) at each site

significant. We can eliminate the confounding effect of fire by analyzing the pre-fire data only.

Prior to the fire, all of the basin characteristics derived from the Streamstats program (USGS 2012) were negatively correlated with the turbidity metrics and the mean percent of drainage area logged. However, turbidity metrics were positively correlated with road attributes (Fig. 6). State highways and USFS roads, not shown in Fig. 6, are negatively correlated with the turbidity variables and rate of harvest. The relatively high correlations among explanatory variables present a dilemma for interpretation of turbidity differences among subwatersheds, but partial correlations aid in sorting out these relationships. All turbidity variables remain positively associated with rate of harvest, even after accounting for the individual basin characteristics or road variables (Fig. 7, top). Almost all of the partial correlations are statistically significant ($p = 0.05$) for the 90th percentile residual and the 90th percentile of sample turbidity, while most are not statistically significant for the mean residual and median sample turbidity. In addition, many of the basin characteristics and road variables remain significantly correlated with turbidity after accounting for rate of harvest (Fig. 7, bottom). In all, 35 of 72 partial correlations shown in Fig. 7 are significant at the 0.05 significance level.

Discussion

Turbidity and Logging Levels

Post-fire erosion is typically greatest during the first year after wildfire (Agee 1990; Debano et al. 1998; Robichaud

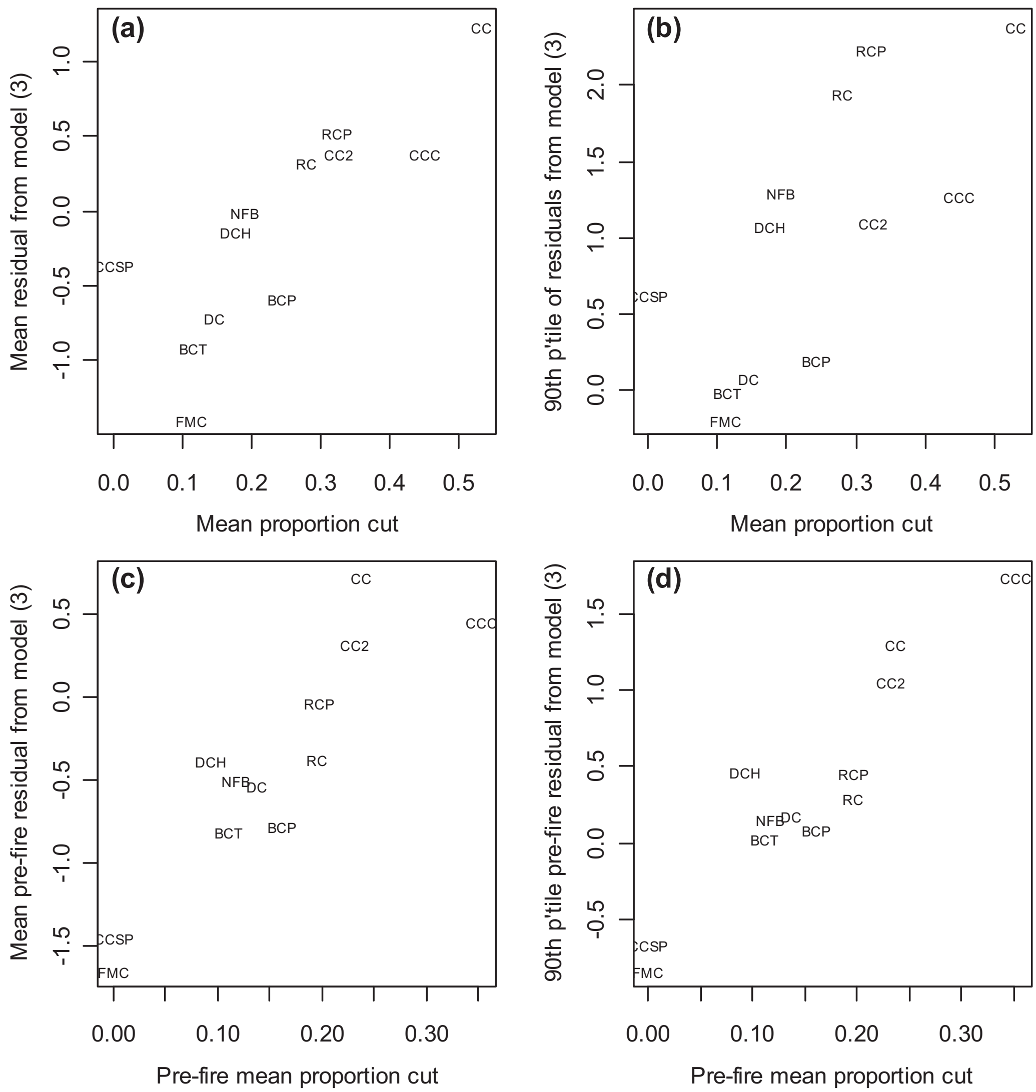

Fig. 5 Scatterplots showing mean and 90th percentile of residuals from model (3), in relation to mean proportion of watershed area harvested. Frames **a** and **b**: full period of record; frames **c** and **d**: pre-fire period. Note the change in scales between upper and lower frames

and Brown 1999). Our observations of greater residuals in the second year strongly suggest that post-fire logging operations had an effect beyond that of fire alone on turbidity levels. Our statistical findings are based on estimated logging rates. Because it is not known precisely when salvage logging occurred at each site, the strength of these results could be limited by the accuracy of the estimates of the rates and areas logged. However, post-fire logging effects are almost certainly underestimated because the post-salvage period was compared with the first post-fire year, which already reflects a progression of post-fire logging (i.e., a lower but non-negligible influence).

In both the pre-fire period and the entire monitoring period, harvesting was positively associated with the median and 90th percentiles of sample turbidities. Regression analysis showed the same effects: after stream discharge, the proportion of watershed harvested explained most of the variation in turbidity. Associations with harvesting are partly confounded with road density, particularly near watercourses, as well as wildfire. All these factors appear to have affected turbidity levels.

The analysis of regression residuals showed significantly increasing turbidity during the monitoring period at 10 of 11 sites affected by fire and post-fire logging. The two sites that have not been burned or logged since 2010 (DC and BCT) showed signs of decreasing turbidity levels starting in 2013. There was also a slight indication of recovery in turbidity levels at site CCC, starting in 2013. Although this trend is not statistically significant, it is consistent with the small fraction of the drainage area affected by fire. Post-fire logging was largely relegated to upslope areas, while a larger portion of the CCC watershed was in recovery mode from earlier harvesting.

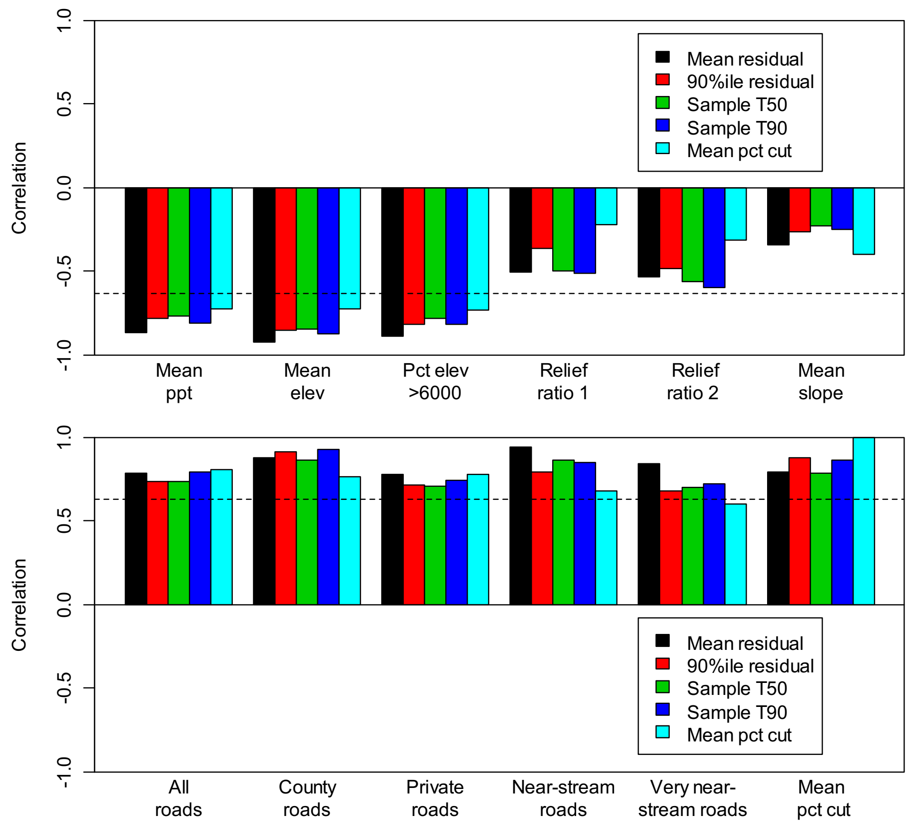

Fig. 6 Pre-fire Pearson correlations of turbidity variables and mean percent harvested with basin characteristics (top), various categories of roads (bottom). Sample T50 and T90 are the median and 90th percentiles of sampled turbidity. Relief ratio 1 is the elevation range divided by the longest flow path. Relief ratio 2 is the elevation range divided by the watershed perimeter. Mean percent harvested is included (bottom right) alongside competing road variables for comparison. Horizontal dashed lines denote significance at alpha = 0.05 for a single test

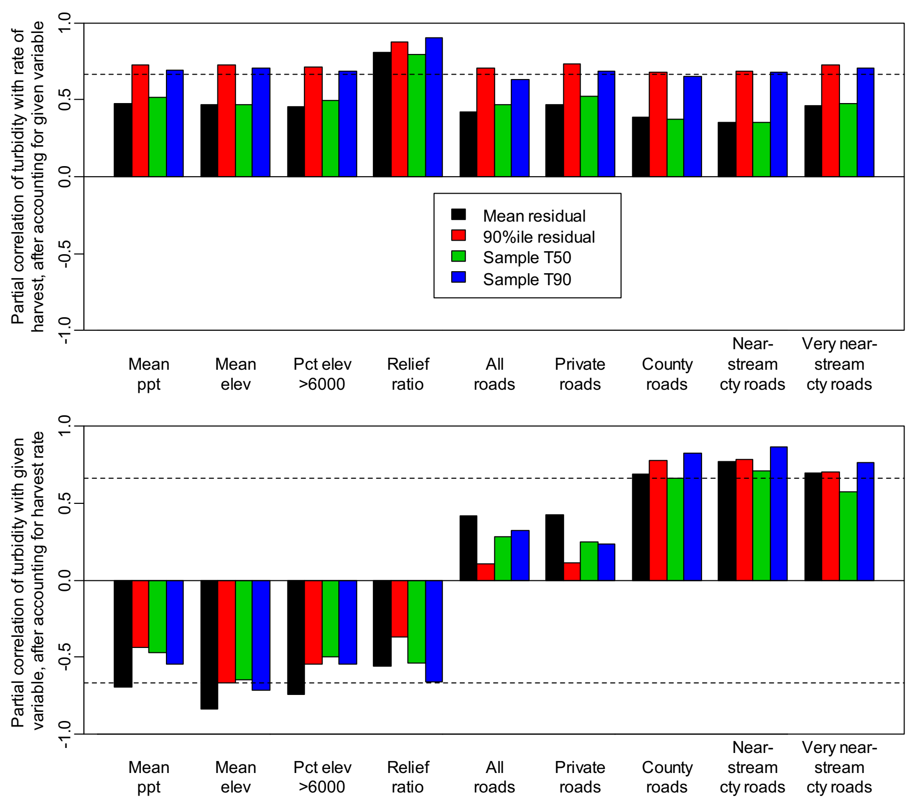

Fig. 7 Pre-fire partial correlations of turbidity variables with rate of harvest, after accounting for basin characteristics and road density (top). Partial correlations of turbidity variables with basin characteristics and road density, after accounting for harvest rate (bottom). Sample T50 and T90 are the median and 90th percentiles of sampled turbidity. Relief ratio is the elevation range divided by the longest flow path. Horizontal dashed lines denote significance at alpha = 0.05 for a single test. In 72 tests at this level with random data, 3.6 would be expected to be significant by chance

Changes in runoff from fire and logging may have contributed to monitored turbidity effects by the cascading effects of reduced transpiration and interception on streamflows (Wondzell and King 2003), which can trigger gully erosion (Reid et al. 2010), and increase bank and bed erosion. Accelerated bank erosion was observed in Battle Creek (CALFIRE et al. 2011) prior to the Ponderosa Fire.

Site-specific studies of sediment sources might help elucidate causes of elevated turbidity in the Battle Creek watershed; however, our results are consistent with previous hillslope-scale studies showing that post-fire logging impedes post-fire revegetation, compacts soils, reduces ground cover, and elevates and extends the duration of runoff and soil erosion after fire (Donato et al. 2006, Wagenbrenner et al. 2015, 2016).

Our results are consistent with those of Klein et al. (2012) which found that turbidity in the northern California Coast Range was most strongly related to the logging levels in the previous 0–15 years. Our analysis of Battle Creek considered the total amount harvested over an approximately 17 year period starting in 1998, prior to which there had been no clearcutting in the watershed. In our study, turbidity declined in three subwatersheds with little or no logging in at least five years. Thus, although the turbidity levels were well correlated with logging in this study, a shorter window such as 0–5 years might be an even better explanatory variable for future analyses.

Our data set cannot separate the impacts of herbicide application, which was used on much of the salvage-logged area outside of riparian zones and some private inholdings within the burned area. While the major loss of cover and vegetation is initially due to fire and salvage logging, herbicides thwart vegetative recovery after disturbance, likely prolonging sediment delivery from logged areas.

While site-specific assessment of logging impacts on erosion was not possible in this study due to lack of access to privately owned timberlands, some sources of increased erosion from logging operations were observable from county roads. Post-fire-logged areas had copious amounts of bare ground with damaged soils that were easily mobilized by runoff and prone to rilling by overland flow (Supplemental Material: Fig. S9). Roadcuts can unravel when exposed to accelerated runoff, especially in burned areas that have not revegetated (Fig. 8, Supplemental Material: Fig. S10). Roadside ditches in many places lacked armoring and showed signs of incision from increased surface runoff from compacted and burned soils, as well as intercepted subsurface flows that are augmented after fire and logging due to reduced evapotranspiration. Some of the elevated turbidity in Canyon Creek is associated with the watercourse-adjacent county road, which serves as a main haul road for logging operations in that watershed. Thus, the effects of roads and harvesting are not only statistically confounded, but interact in ways that are not physically separable: much of the road erosion is induced by harvesting activities.

The magnified vulnerability of hillslopes to surface erosion after logging may be transiently mitigated by contour ripping, but gains are likely offset over the long term by the associated ground cover loss and delayed regrowth, which

Fig. 8 Roadcut bank erosion initiated or aggravated by overland flow from burned and harvested areas upslope, September 2014

is prolonged in Battle Creek by widespread pre-emergent herbicide application designed to prevent seed germination.

Potentially Confounding Factors

Numerous studies have shown that roads are major sediment sources in many environments (Gucinski et al. 2001). The associations of turbidity with logging levels, especially post-fire salvage logging, in our study appear robust, but findings also suggest that turbidity was influenced by erosion and runoff from roads. Roads are an integral part of the logging operations applied since 1998 in Battle Creek. Over 550 clearcut patches typically 8–10 ha in size have been created and all are accessed by roads. Road density is highly correlated with harvesting levels in this study and is likely one reason for the robust relationship between logging and turbidity.

Road activities, including construction, reconstruction, and increased traffic, occur in conjunction with logging, making it difficult to separate their effects. Increased road traffic for log haul increases road erosion and subsequent delivery of fine sediment to streams (Reid et al. 1981; Reid 1998), particularly during winter operations on wet roads. Runoff from compacted hillslopes can increase erosion on road cutbanks (e.g., Fig. 8, Supplemental Material: Fig. S10). Hence reducing the area under THPs would likely also reduce the impact of roads. However, the partial correlation analysis shows that rate of harvest is well-related to higher percentiles of turbidity even after accounting for the variation explained by road density, regardless of the type of road considered or its proximity to a stream (Fig. 7).

Elevation can indirectly affect erosion and turbidity. Snow is the dominant form of precipitation at higher elevations in the watershed. Such areas may have lower levels of surface erosion, because they are not subject to rainsplash and snowmelt runoff tends to be less intense than that from rainfall. Most privately owned timberland in the study area is at 900–1500 m in elevation. In the past decade, there has been very little timber harvest at the higher elevations on federal lands (James and MacDonald 2012). Thus, all of the elevation-related variables are inversely correlated with mean percent cut (Fig. 6, top). However, the partial correlation analysis showed that harvesting explains substantial variability in turbidity even after accounting for annual precipitation, elevation, and relief ratio (Fig. 7, top).

Analyses assessing potential logging impacts on turbidity among sites (Fig. 5; Table 4) are inherently vulnerable to confounding by site-specific factors including elevation, precipitation form, topography, geology, and the location and density of roads. However, analyses of variation at individual sites (Fig. 4) are not confounded by fixed factors related to geology, soils, and topography.

Associations of turbidity with time or harvest rate at an individual site could be influenced by water diversions and local variations in precipitation that are not accounted for by discharge measurements at the Coleman station. However, such variations are not expected to systematically induce multiyear trends. The statistical findings could also be influenced by other human activities not examined in this study. However, ranching and agricultural uses affect only a small part of the land base (Supplemental Material: Fig. S1), and recreational activity in the uplands is low-impact.

The Canyon Creek spring (CCSP) differs from the other sites in having no surface watershed, although its turbidity was apparently affected by logging-related disturbances. Omitting it from the analyses would have strengthened some of the tests of association, since it plots higher than expected for a watershed with zero harvest (Fig. 5a, b).

Water Quality and Ecological Impacts

Coefficients in the fitted model (3) indicate that logging of 50% of a drainage is likely to cause a five-fold increase in turbidity, while completely logging a drainage is likely to increase turbidity by a factor of 23. This is a significant water quality concern as peak turbidity levels in streams affected by wildfire and post-fire salvage logging now commonly exceed 100 NTU and occasionally exceed 1000 NTU (Fig. 3). At these levels, turbidity can have adverse effects on salmonids (Rhodes et al. 1994) and a host of downstream beneficial uses of water including irrigation and drinking water.

Due to the lack of continuous monitoring of turbidity in this study, the duration and magnitude of elevated turbidity at monitoring sites is uncertain. However, independent monitoring in the Battle Creek watershed (USFWS 2015) documented major increases in fine sediment levels in salmonid spawning habitats and major losses of pool volume and quality in 2014 and 2015 after post-fire logging. It is likely that pool loss negatively affected salmonids because the quality, volume, and frequency of pools are important for salmonids at multiple lifestages (McIntosh et al. 2000). Increased levels of fine sediment reduce salmon and steelhead survival (Suttle et al. 2004; Cover et al. 2008). Our analysis indicates that logging, particularly after the severe wildfire, likely contributed to the recent degradation of spawning and pool habitats in the Battle Creek watershed.

Cumulative Impacts

Emergency rules in California do not require a consideration of cumulative impacts when permitting post-fire salvage logging. However, cumulative impacts are probable when an area is logged, roaded, burned, salvage-logged, and subjected to herbicide, because BMPs cannot completely prevent accelerated sediment delivery (Ziemer and Lisle 1993; Lewis et al. 2001; GLEC 2008; Klein et al. 2012; Wagenbrenner et al. 2015, 2016). Thus, a high temporal concentration of projects in space within a watershed is likely to degrade water quality and aquatic ecosystems via sedimentation. Such negative impacts might be reduced or avoided by limiting the rate of logging in watersheds. This approach has been taken by California state agencies in Elk River and Freshwater Creek (NCRWQCB 2006) where downstream residents have been impacted by aggradation and flooding.

Conclusions

Battle Creek contains important cold-water habitat for threatened and endangered runs of Chinook Salmon in the Sacramento River system. About 48% of privately owned timberlands in the North Fork (NFB drainage) have been logged since clearcutting began in 1998. In the Ponderosa fire area >11,000 ha have been affected by a combination of clearcutting, roads, wildfire, post-fire logging, and herbicide. Each of these factors appears to have been important in elevating turbidity levels. Our analysis of turbidity data from 2009 to 2015 at 13 watershed locations indicates that the sites with the most harvesting and highest road densities had the highest turbidity before the fire and throughout the entire monitoring period. Turbidity remains strongly associated with harvesting after statistically accounting for road effects. Importantly, roads are an inseparable part of logging operations. Turbidity increased over the measurement period at ten sites, during the pre-fire period at four sites, and during the post-fire period (reflecting the influence of post-fire logging) at six sites. Extreme turbidity measurements (>7 times the average value for a given flow condition) were rare before the fire, but became more frequent (5% of measurements) in the year after the fire, and subsequently more than doubled in frequency in the first season after salvage logging was completed. Turbidity decreased in watersheds that were unaffected by the fire and had not been harvested since 2010.

Our results are consistent with previous assessments of the effects of post-fire logging on water quality (Kattelmann 1996; Beschta et al. 2004; Smith et al. 2012; Wagenbrenner et al. 2016). Despite site-specific application of BMPs, ground-based logging with high road densities was strongly associated with the magnitude of turbidity and sediment-related aquatic impacts, apparently forestalling the post-fire recovery of water quality. These findings suggest that adverse cumulative impacts on water quality may not be completely avoidable using current BMPs without also limiting the rate and total area affected by logging operations.

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Compliance with ethical standards

Conflict of interest Jack Lewis received funding from the Battle Creek Alliance in 2015 for an unpublished analysis of these data. Lewis' updated analyses and composition of this article was not funded. Curtis Bradley contributed GIS analysis while employed by the Center for Biological Diversity (CBD) and Jon Rhodes received a small fee from CBD for his assistance.

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