An Analysis of Turbidity in Relation to Timber Harvesting in the Battle Creek Watershed, northern California
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Prepared by

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INTRODUCTION

The Battle Creek watershed in northern California drains 357 mi^2 on the west side of Lassen National Park and enters the Sacramento River between Redding and Red Bluff. Battle Creek is a drought-resistant, spring-fed system that is important to species such as winter-run and spring-run Chinook salmon and steelhead that are dependent on cool-water habitats. Historically, the watershed was uniquely important for the diversity and size of its Chinook salmon populations, which are now at remnant levels due to changes in land and water uses, especially water diversions for hydroelectric power. Winter-run Chinook are listed as endangered under the federal and state Endangered Species Acts and spring-run Chinook are listed as threatened under both Acts. The Battle Creek Salmon and Steelhead Restoration Project is in the process of restoring about 48 miles of habitat through modification of hydroelectric project facilities, operations, and management. Timber harvesting in Battle Creek began in the late 19th century but has intensified since 1998, when clearcutting became the dominant silvicultural method. In the privately owned portion of the watershed downstream from the National Park and Lassen National Forest, the 2012 satellite image (Figure 1a) reveals a checkerboard pattern of clearcuts as the most conspicuous feature of the landscape. Between 1998 and 2012, roughly 21,000 acres of the watershed were designated for harvest under Timber Harvest Plans. In 2012, the Ponderosa fire burned over 27,000 acres (Figure 1b), most of which was salvage logged in the following year (Figure 2).

Kier Associates (2009) attributed a degradation of aquatic habitat conditions (fine sediment and pool habitat) for salmonids in Battle Creek to cumulative effects from timber harvesting. Myers (2012) utilized a variety of data sources to develop a conceptual flow and transport model to help in interpreting current CWEs. He warned that the high rates of harvesting may increase extreme floods and concomitant sedimentation, due to changes in evapotranspiration, snowpack and runoff, particularly during rain-on-snow events; and that the effects of recent logging have probably not yet been realized due to relatively dry conditions in the past several years. Detailed descriptions of the climate, soils, geology, topography, vegetation, stream morphology and aquatic conditions can be found in the Kier and Myers reports and will not be repeated here.

The Battle Creek Alliance (BCA) began measuring turbidity, water temperature and pH at 13 locations in the watershed in December 2009. Myers (2012) took a brief look at the first two years of data collected. Four and a half years of data have now been collected and this report summarizes new analyses relating the turbidity data to the intensity of harvest at each of the measurement sites.

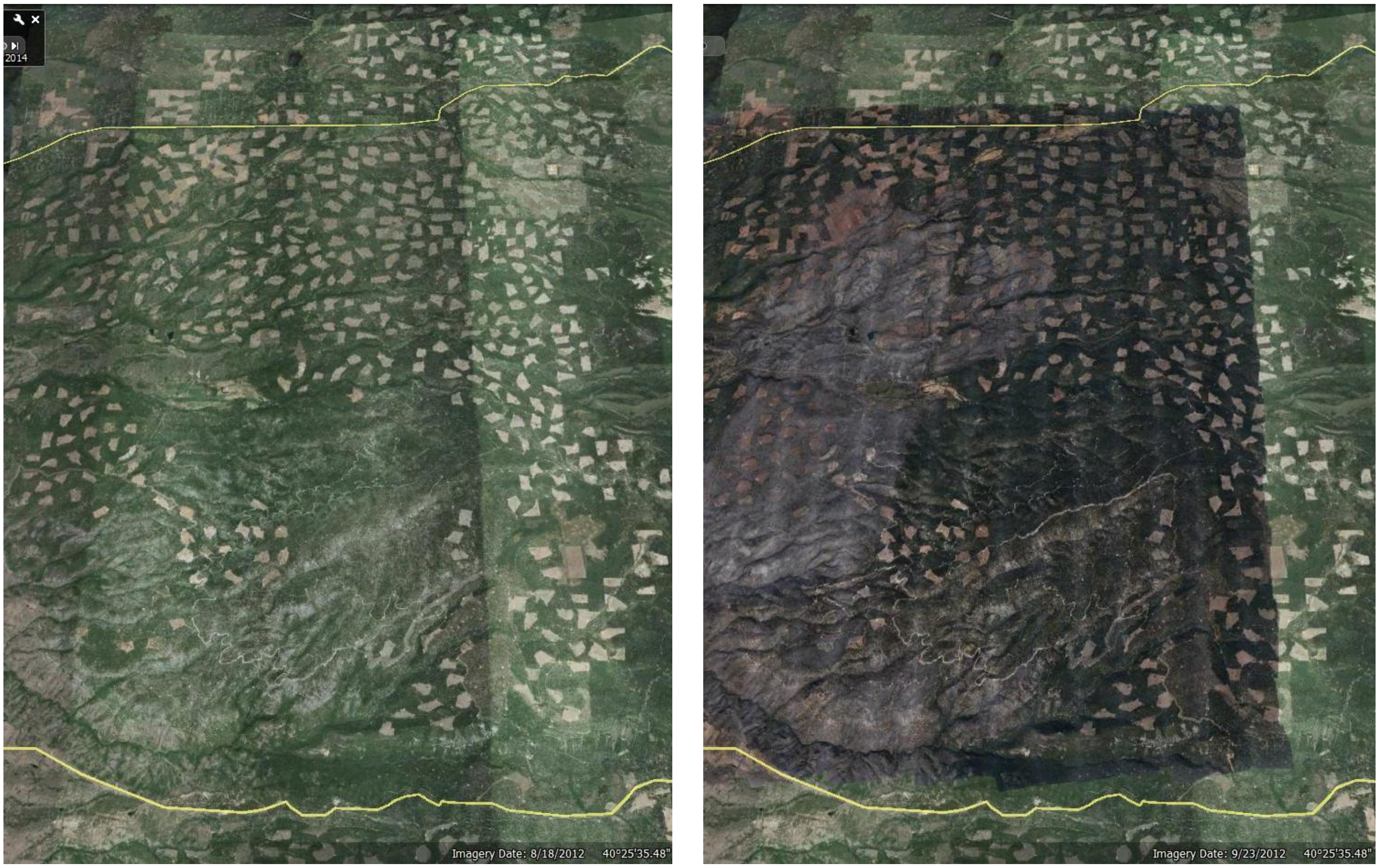

Figure 1. Google Earth composite images before and after 2012 Ponderosa fire: Jul 9 (left) and Sep 12 (right). Yellow lines are State Highways 36 (bottom) and 44 (top). The town of Manton is just beyond the left edge.

Methods

The majority of the measurement sites are within and below the industrial timberland owned by Sierra Pacific Industries (SPI). Included are higher and lower locations on 4 tributaries of Battle Creek, as well as one site each of the North and South Fork of Battle Creek (Table 1, Figure 3). Drainage areas in Table 1 are based upon surface topography, but are not as informative as they might be in other environments due to the porous nature of the bedrock in the area, and a great number of water diversions. The volcanic rock in the area allows a larger portion of the incoming rainfall to percolate through the soil to feed aquifers which may in some cases emerge in different surface drainage basins. Water diversions include consumptive uses of water such as irrigation, fire control, dust control, stock watering and domestic withdrawals. Undoubtedly the largest diversions are for PG&E's hydroelectric dams and powerhouses. A series of reservoirs and canals divert and reroute waters from a dozen locations. From Water Diversion Statements and Licensee Reports, 2003-2011, I calculated that an average of 106,000 acre feet is diverted annually from the North Fork to the South Fork above site SFB. This enhances the mean annual flow at SFB by 87%. Thus measurements at SFB could reflect, to a significant extent, conditions in the NFB watershed. Of the total diverted flow, 75,600 acre feet is withdrawn from above site NFB, about 52% of the annual flow at that site. (Annual flows at NFB and SFB are estimated roughly, based on watershed areas relative to the gage at Coleman Fish Hatchery). Because the water quality at SFB is so strongly influenced by diversions from the North Fork, SFB has been omitted from analyses that relate water quality to harvesting.

Figure 2. Digital Globe image of salvage logged area, July 4, 2014, nearly 2 years after the Ponderosa Fire.

The measurement period analyzed in this report is from Dec 30, 2009 to July 3, 2014. Turbidity is measured using a Hanna Instruments HI 98703 portable turbidimeter. According to the manufacturer, the HI 98703 meets and exceeds the requirements of the USEPA Method 180.1 for wastewater and Standard Method 2130 B for drinking water. It is designed for accuracy and sensitivity at very low turbidity levels. Equipment is calibrated monthly. BCA collects data throughout the watershed 37-49 days per year, with all sites usually being sampled on the same day, typically at 7-12 day intervals. During periods of rain and/or snow, samples are usually collected after storms, often on consecutive days or every other day. Samples are dipped from a location where the water is rushing. The first dip is discarded after rinsing the container with it; the second dip is retained and transferred to the turbidimeter sample vial, and measured following the manufacturer's procedures. Since manual sampling is constrained by logistics and daylight, relatively few samples are collected on the rising limbs of storms when turbidity is likely to be at its maximum.

Table 1. BCA sampling sites and characteristics

Site ID	Name	Elev (ft)	Drainage Area (ac)	Percent logged	Watershed Notes
BCT	Bailey Creek upper	3990	10,333	13.1	above fire, mostly federal lands
BCP	Bailey Cr lower	2300	20,590	33.9	just below a major spring
CCC	Canyon Cr upper	3760	321	40.2	an intermittent tributary to Canyon Cr
CCSP	Canyon Cr spring	3760	0	0.0	the source of Canyon Creek: a spring with no surface catchment
CC2	Canyon Cr middle	3490	1,040	80.7	100% burned and salvaged below CCC
CC	Canyon Cr lower	3160	1,871	89.2	100% burned and salvaged below CCC
RC	Rock Cr upper	3090	11,984	40.4	lower third was heavily burned
RCP	Rock Cr lower	2330	14,782	48.9	includes CC and RC drainages
DC	Digger Cr upper	3440	13,527	16.0	above fire and salvage logged area
FMC	Digger Cr trib	3080	<10	100.0	an intermittent tributary to Digger Cr
DCH	Digger Cr lower	2580	22,458	27.0	just downstream of fire boundary
NFB	North Fork Battle	1920	91,205	28.2	includes Bailey and Rock Cr but not Digger
SFB	South Fork Battle	940	76,472	13.2	last to be harvested, receives NF diversions

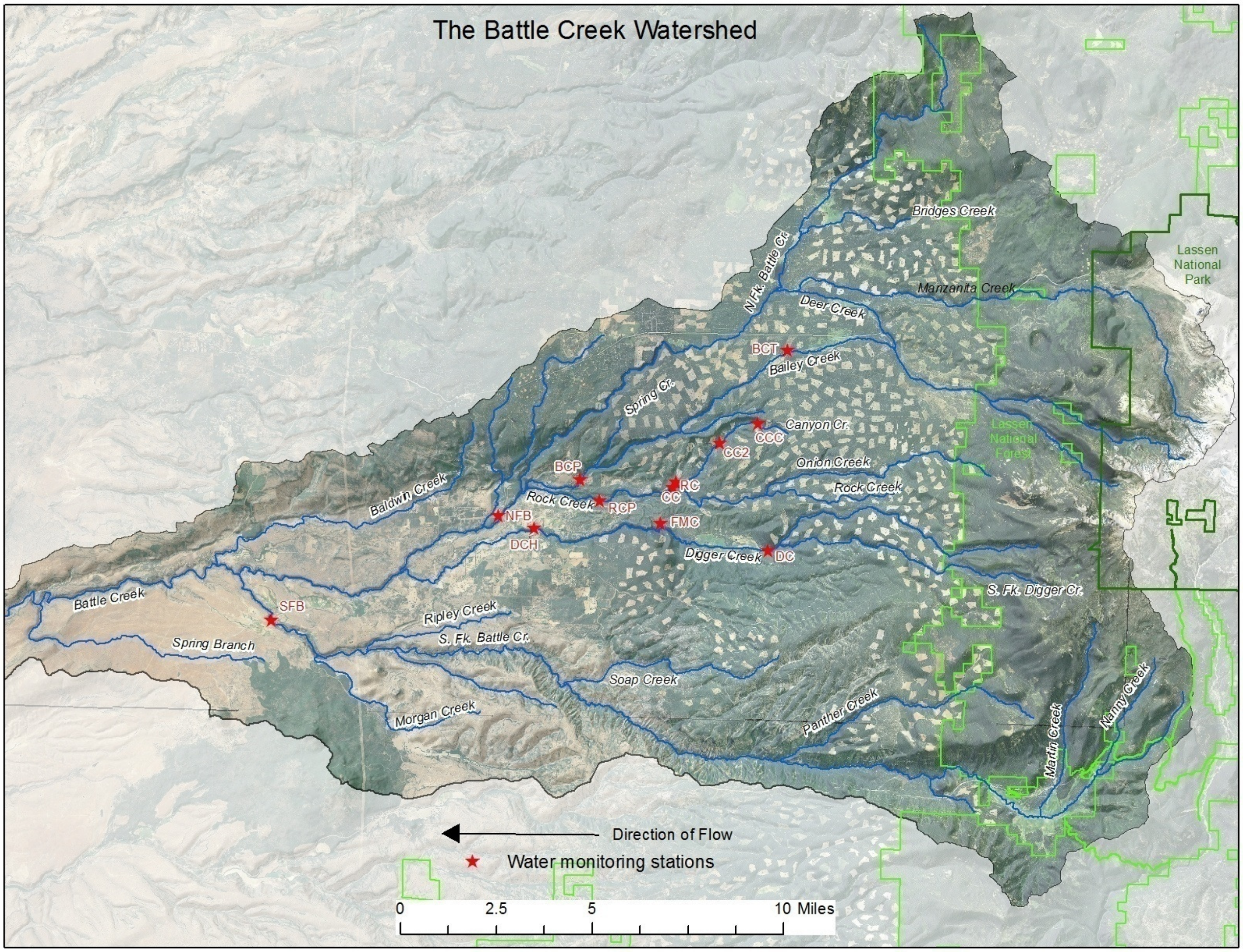

Figure 3. BCA sampling sites. Checkered appearance is due to clearcutting. Image was taken prior to the 2012 Ponderosa fire, hence does not include salvage logging and more recent harvesting.

The timing and amount of harvesting in each drainage were not readily available, except for the total acreages by THP; a significant part of this effort was deriving that information. Watershed boundaries and areas draining to each sampling site were GIS-derived by Curtis Bradley (Center for Biological Diversity) from DEMs for the area. The harvested proportion in each drainage was estimated from Google Earth images which are available at irregular intervals that vary by location. The clearcuts are fairly uniform in size, averaging 20 to 25 acres. An average size clearcut was calculated for each THP based on the total THP acreage and number of cutblocks. The procedure assumes that harvesting for roads and other silvicultural methods was conducted concurrently in proportion to the clearcutting. When new cut blocks appeared on the satellite images, the number of blocks in each THP was counted by drainage, multiplied by the average size cutblock for that THP, and summed to determine the newly harvested area in each drainage. The 2012 Ponderosa Fire killed nearly all of the merchantable-size trees and nearly all were salvage logged within a year (Figure 2). The salvage logged area was calculated for each drainage, as the SPI acreage within the fire boundary (Figure 4) minus the previously harvested area within the fire boundary. Using these procedures, the logged proportions of each watershed were estimated at the date of each Google Earth image (Table 2). The latest available image covering all harvested areas in the watershed was taken immediately after the Ponderosa fire on Sep 23, 2012. The last two lines of the table incorporate assumptions that (1) salvage logging was completed by Sep. 21, 2013, and (2) any harvesting on THPs that had not been completed when the fire occurred was resumed after the salvage logging and will be completed by this fall (Nov. 14, 2014, expiration date for the Blue Ridge THP). Except at the Canyon Creek sites, the 2012 proportions harvested are lower than they appear from visual inspection of the satellite images (e.g. Figures 1,3) because of the large unlogged areas upstream in National Forest and National Park Lands. Table 3 shows the logged proportions, excluding upland federal lands.

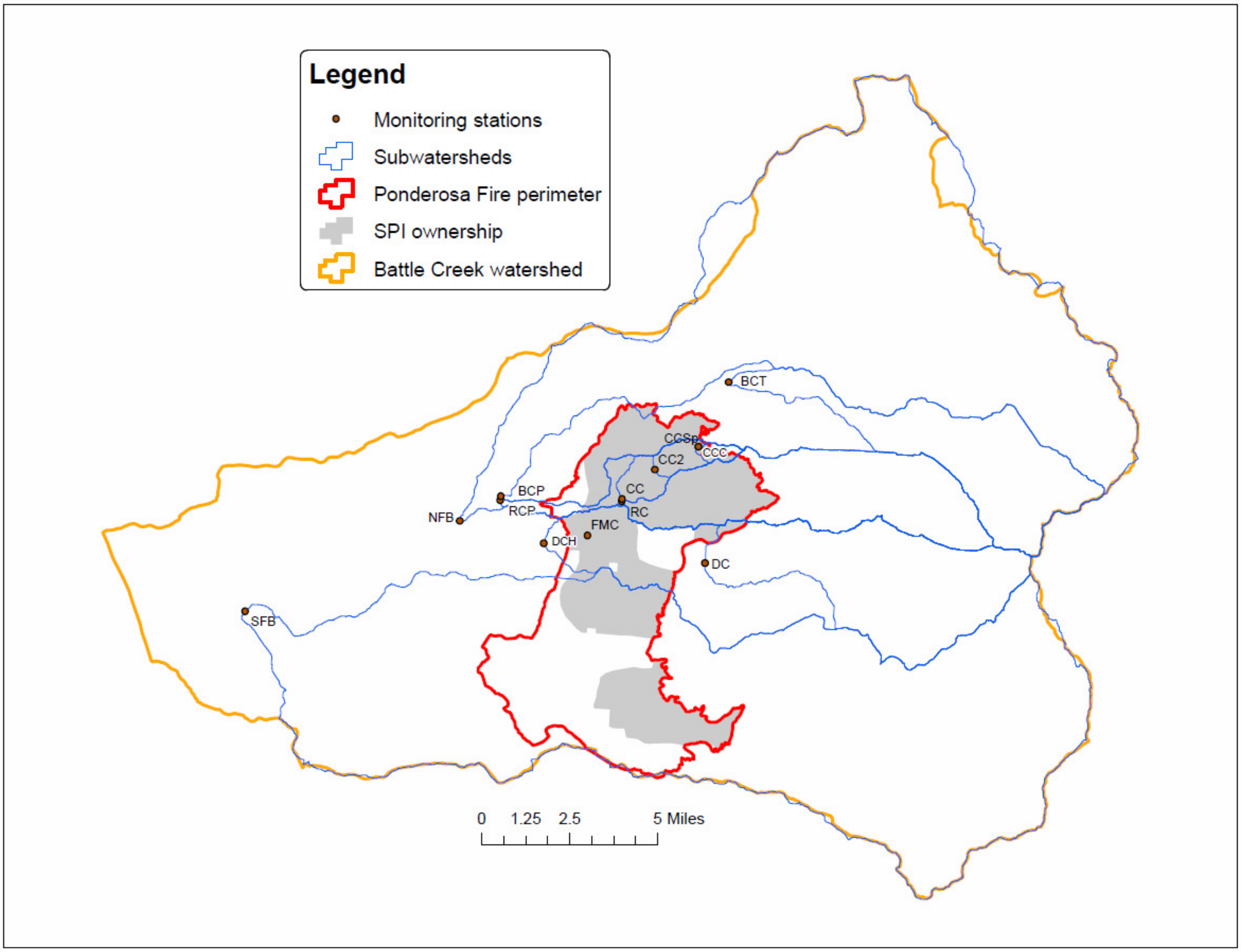

Figure 4. BCA sampling sites, drainage boundaries (blue), fire boundary (red), and SPI salvage logging (gray). SPI ownership is shown only within the fire perimeter.

Table 2. Proportions of drainage areas harvested between 1998 and specified date

Image date	BCT	BCP	CCC	CC2	CC	RC	RCP	DC	FMC	DCH	NFB	SFB
5/24/2009	0.054	0.129	0.353	0.232	0.238	0.196	0.197	0.072	0.000	0.043	0.108	0.035
4/24/2010	0.102	0.156	0.353	0.232	0.238	0.196	0.197	0.126	0.000	0.076	0.115	0.035
7/21/2010	0.115	0.164	0.353	0.232	0.238	0.196	0.197	0.142	0.000	0.089	0.117	0.037
7/27/2011	0.115	0.164	0.353	0.232	0.238	0.196	0.197	0.142	0.000	0.089	0.117	0.037
7/29/2012	0.115	0.168	0.353	0.232	0.238	0.196	0.197	0.147	0.000	0.124	0.122	0.053
8/18/2012	0.115	0.168	0.353	0.232	0.238	0.196	0.197	0.147	0.000	0.124	0.122	0.055
9/23/2012	0.115	0.186	0.353	0.232	0.238	0.196	0.197	0.147	0.000	0.124	0.172	0.055
9/21/2013	0.115	0.297	0.402	0.807	0.892	0.404	0.473	0.153	1.000	0.231	0.268	0.124
11/14/2014	0.131	0.339	0.402	0.807	0.892	0.404	0.489	0.160	1.000	0.270	0.282	0.132

Table 3. Proportions of drainage areas, excluding upstream federal lands, harvested between 1998 and specified date

Image date	BCT	BCP	CCC	CC2	CC	RC	RCP	DC	FMC	DCH	NFB	SFB
5/24/2009	0.216	0.207	0.353	0.232	0.238	0.285	0.264	0.150	0.000	0.063	0.183	0.047
4/24/2010	0.406	0.250	0.353	0.232	0.238	0.285	0.264	0.265	0.000	0.111	0.195	0.047
7/21/2010	0.458	0.263	0.353	0.232	0.238	0.285	0.264	0.298	0.000	0.129	0.199	0.050
7/27/2011	0.458	0.263	0.353	0.232	0.238	0.285	0.264	0.298	0.000	0.129	0.199	0.050
7/29/2012	0.458	0.269	0.353	0.232	0.238	0.285	0.264	0.308	0.000	0.181	0.207	0.072
8/18/2012	0.458	0.269	0.353	0.232	0.238	0.285	0.264	0.308	0.000	0.181	0.207	0.075
9/23/2012	0.458	0.298	0.353	0.232	0.238	0.285	0.264	0.308	0.000	0.181	0.292	0.075
8/27/2013	0.458	0.476	0.402	0.807	0.892	0.587	0.633	0.322	1.000	0.338	0.454	0.168
11/14/2014	0.521	0.543	0.402	0.807	0.892	0.587	0.655	0.337	1.000	0.394	0.478	0.180

The proportion harvested was estimated at the time of each BCA measurement by interpolating linearly between the values in Table 2. The procedure assumes that harvesting occurred at a constant rate throughout the year. Winter operations have been routinely conducted in the watershed so the assumption is the best plausible approximation of what occurred based on the available information.

Analysis

Box and whisker plots (Figure 5) depict key features of the distributions of turbidity at each sampling site.

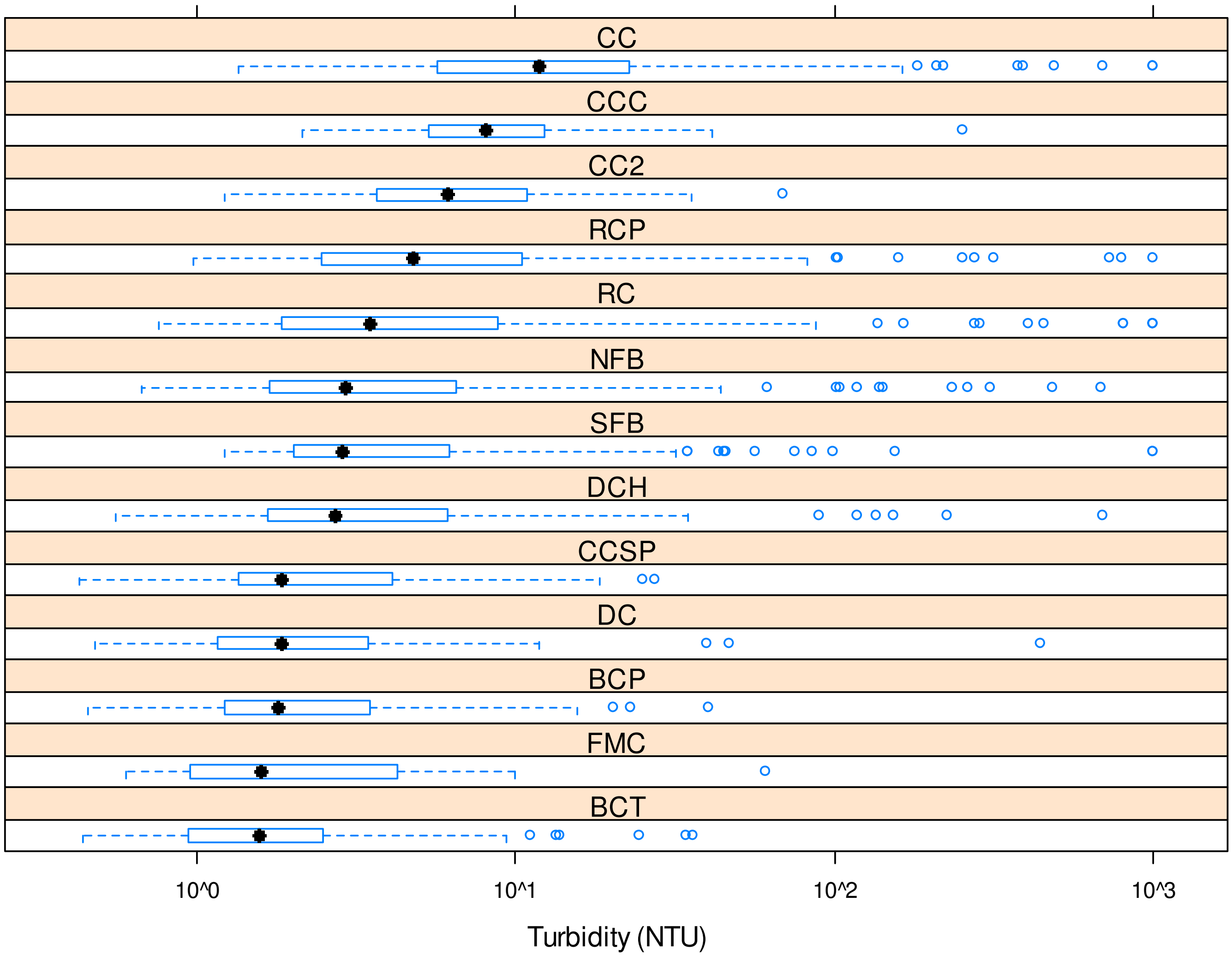

Figure 5. Box and Whisker plots of turbidity at each sampling site. The black dot is the median turbidity. The blue rectangle defines the middle 50% of the data, i.e. 25% of the measurements are below and 25% are above the blue rectangle. The dashed lines extend from the blue box in each direction to the last point within 1.5 times the interquartile range (1.5 boxes). And the hollow circles are all outliers beyond 1.5 interquartile ranges. The strings of points to the right indicate skewed long-tailed distributions.

Table 4 shows the median and mean proportions harvested in the areas draining to each sampling site, over all water quality samples. The means are used in many of the analyses to follow. CCSP is measured where a spring emerges from the ground (the source of Canyon Creek), so the harvested proportion of its watershed is assumed to be zero, even though the area has been disturbed. SFB has a small proportion harvested, but its waters are contaminated by diversions from the more heavily disturbed North Fork. The sites in Canyon Creek have had the highest proportion of their drainages logged.   Other than for Canyon Creek, the values in Table 4 are diluted by unlogged portions of the watersheds upstream in Lassen National Park and Lassen National Forest. Table 5 shows the areas harvested as of July 2014, as proportions of the watershed areas downstream of federal lands in addition to showing them as proportions of the entire watersheds. Site CCSP is a spring and may have been affected by salvage logging, but its watershed area and proportion harvested are coded as zero. Site FMC was unlogged prior to the Ponderosa fire, after which it was salvage logged. After alteration of the channel by equipment and subsequent drought, site FMC is now usually dry; measurements were discontinued there shortly after the fire.

Table 4. Median and mean areas harvested, as a proportion of the area draining to each sample site, for all water quality samples. Statistics are computed for each site from the dates on which its turbidity was measured.

	BCT	BCP	CCSP	CCC	CC2	CC	RC	RCP	DC	FMC	DCH	NFB	SFB
median	0.115	0.168	0.000	0.353	0.232	0.238	0.196	0.197	0.147	0.000	0.124	0.121	0.053
mean	0.115	0.222	0.000	0.369	0.244	0.475	0.270	0.292	0.145	0.028	0.150	0.177	0.073

Table 5. Estimated areas harvested by July 2014 as a proportion of (1) watershed downstream from Lassen National Park and Lassen National Forest, and (2) entire watershed. Statistics are computed for each site from the dates on which its turbidity was measured.

Watershed	BCT	BCP	CCSP	CCC	CC2	CC	RC	RCP	DC	FMC	DCH	NFB	SFB
downstream	0.501	0.522	0.000	0.402	0.807	0.892	0.587	0.648	0.332	1.000	0.376	0.470	0.176
entire	0.126	0.326	0.000	0.402	0.807	0.892	0.404	0.484	0.158	1.000	0.258	0.278	0.129

The median sample turbidity at each sampling location is positively and significantly associated with the median and mean proportions harvested from Table 4 (Figure 6 and Table 6). In both of these plots the 3 Canyon Creek sites (CCC, CC2, and CC) exhibit the highest turbidity. These are also the most heavily logged drainages. The Rock Creek sites (RC and RCP) exhibit the next highest turbidity and rank next behind the Canyon Creek sites in intensity of harvest. The 90th percentile sample turbidity (i.e. the value exceeding 90% of the sample turbidities) is also positively and significantly associated with the mean proportion harvested (Figure 7 and Table 6). The 90th percentile sample turbidity is again highest for CC, but CCC and CC2 rank behind RC, RCP, and NFB. Hence, while typical flows at the Canyon Creek sites are the most turbid, the higher/muddier flows at the upper Canyon Creek sites appear to be less turbid than corresponding flows in Rock Creek or NF Battle Creek.

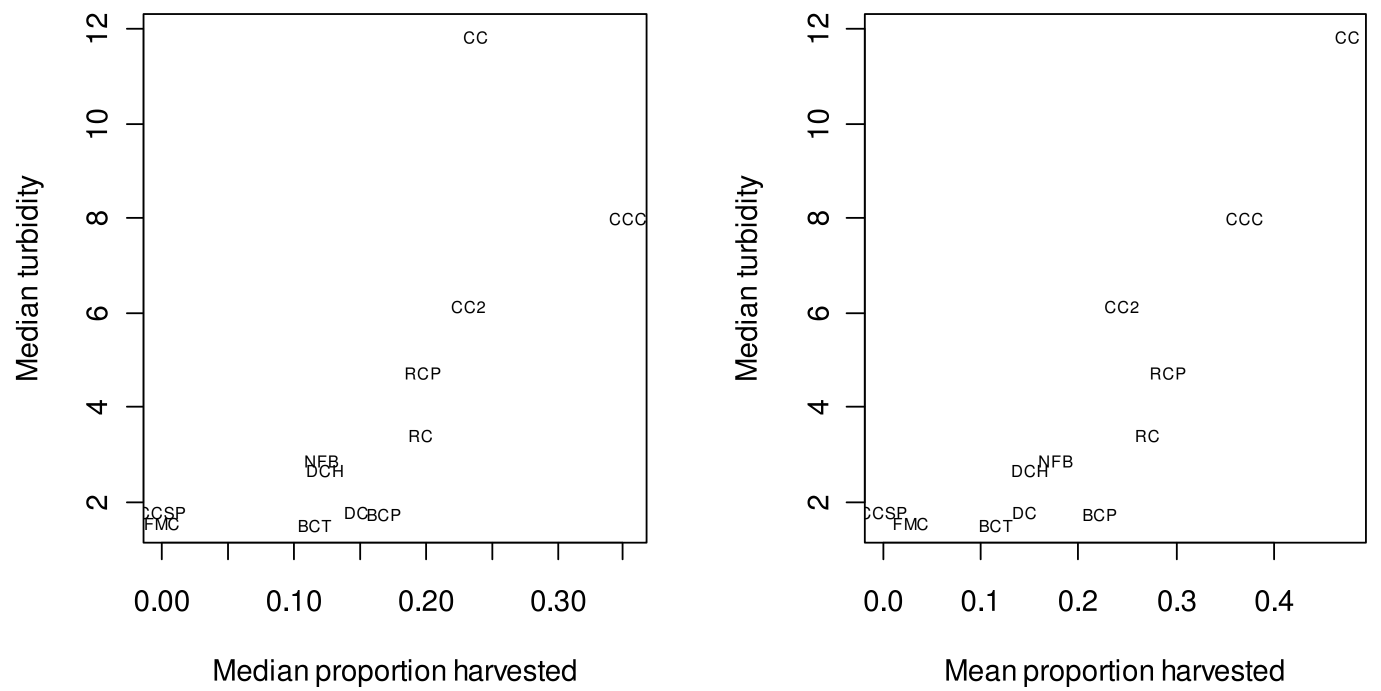

Figure 6. Scatterplots showing median sample turbidity in relation to proportions of area harvested.

Table 6. Associations between various measures of turbidity and average proportion harvested in each watershed. The Pearson correlation varies from -1 for a perfectly negative linear association to +1 for a perfectly positive linear association, with 0 indicating no association. Significance tests for the Pearson correlation assume normally distributed data. Kendall's tau is a non-parametric measure of association that also varies from -1 to +1, but it is based on sample ranks rather than raw values. Kendall's tau does not require normally distributed data and, with non-normal data, the significance tests are more powerful for detecting relationships than the better known Pearson correlation. The p-values indicate the probability that an association could have occurred by chance; values less than 0.05 are generally considered to indicate statistically significant relationships. Rows 4 to 8 pertain to model-generated daily turbidity values. The last row of the table refers to ranks from the Friedman rank-sum test for observations matched by date (prior to the Ponderosa fire) from all sites but CCSP and FMC.

Harvest variable	Turbidity variable	Pearson correlation	p-value	Kendall's tau	p=value
Median proportion harvested	Median sample turbidity	0.719	0.0084	0.657	0.0031
Mean proportion harvested	Median sample turbidity	0.878	0.0002	0.697	0.0010
Mean proportion harvested	90th percentile sample turbidity	0.799	0.0018	0.606	0.0054
Mean proportion harvested	Median daily turbidity	0.904	0.0001	0.788	0.0001
Mean proportion harvested	90th percentile daily turbidity	0.843	0.0006	0.788	0.0001
Mean proportion harvested	Median Dec-May daily turbidity	0.906	0.0000	0.788	0.0001
Mean proportion harvested	90th p'tile Dec-May daily turb	0.831	0.0008	0.758	0.0002
Mean proportion harvested	99th p'tile Dec-May daily turb	0.769	0.0034	0.727	0.0005
Mean proportion harvested	Mean regression residual	0.886	0.0001	0.788	0.0001
Mean proportion harvested	Mean turbidity rank	0.811	0.0044	0.644	0.0091

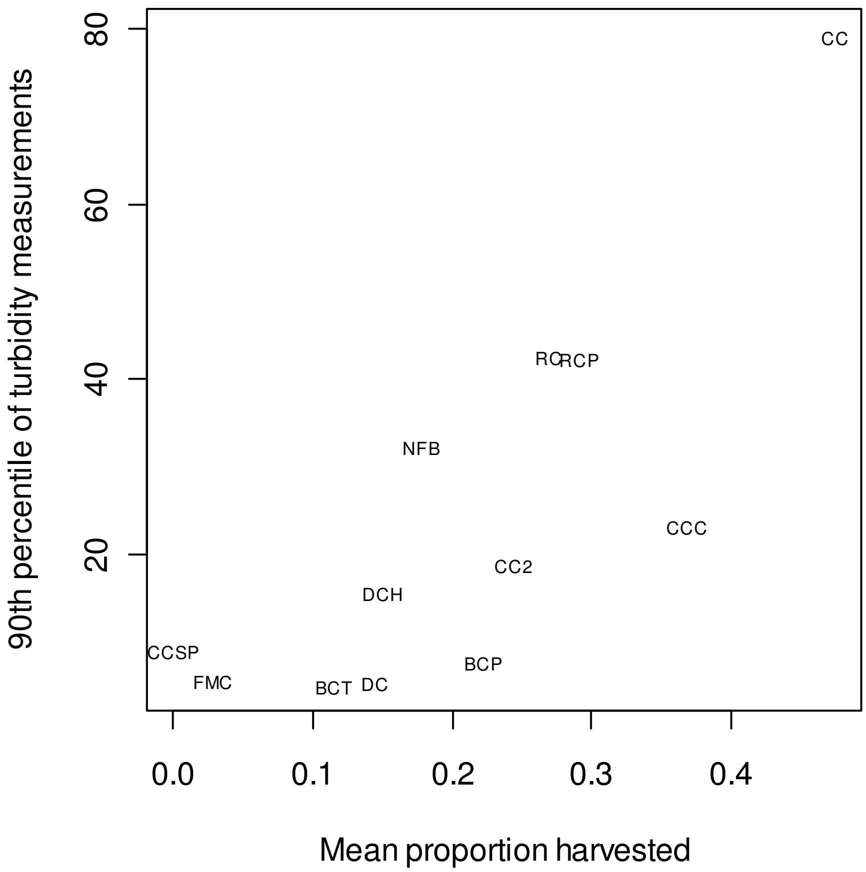

Figure 7. Scatterplot showing 90th percentile sample turbidity in relation to mean proportion harvested.

The comparisons in Figures 6 and 7 are reasonable because all sites were generally sampled on the same days and there is no systematic relation between turbidity and the time of day sampled. However, sample turbidities are not representative of the full range of ambient turbidity because measurement times were constrained by logistics. Therefore I developed a regression model to predict daily turbidity from mean daily discharge (MDQ) at the USGS Coleman Fish Hatchery gaging station downstream from the confluence of the North and South Forks of Battle Creek. Instantaneous discharge was not used because, for a variety of reasons, the Coleman Hatchery hydrographs are very unlikely to be well-synchronized with those at the sampling sites. There was a positive relationship between turbidity and daily mean discharge at all sampling sites (Figure 8). A turbidity model was developed using MDQ as well as the one-day change in MDQ (denoted MDQ1), which helps to distinguish periods when flow is increasing from those when flow is decreasing. All sites were combined in the model but separate intercepts and coefficients for MDQ were estimated for each sampling site. The model explains about 54% of the variation in log(turbidity) and was used to predict daily turbidity for the entire study period. I then computed percentiles of daily turbidity in order to better represent the full range of turbidity conditions for the study period, not just the dates sampled. Both the 50th and 90th percentiles of daily turbidity are positively and significantly correlated to mean proportion harvested (Figure 9 and Table 6). I also computed percentiles of December-to-May daily turbidity (Figure 10 and Table 6), mainly for comparison with Klein et al (2011), who published results for the 90th percentile, which was referred to as the 10% exceedence value in that paper. Based on the 10% exceedences, turbidities in Battle Creek are lower than those reported for managed watersheds in the coast Range. That is not surprising because of Battle Creek's much more subdued topography, harder bedrock, porous soils, and lower natural erosion rates. However, results still are not strictly comparable, since statistics are for different years, and the Klein analysis was based on essentially continuous measurements from instream turbidimeters. Tests of association with harvesting were significant for all percentiles of daily turbidity (Table 6, rows 4 to 8). These are not independent tests since all the daily turbidity values are predictions using the MDQ model, so they all reflect the relative rankings of the coefficients in that model.

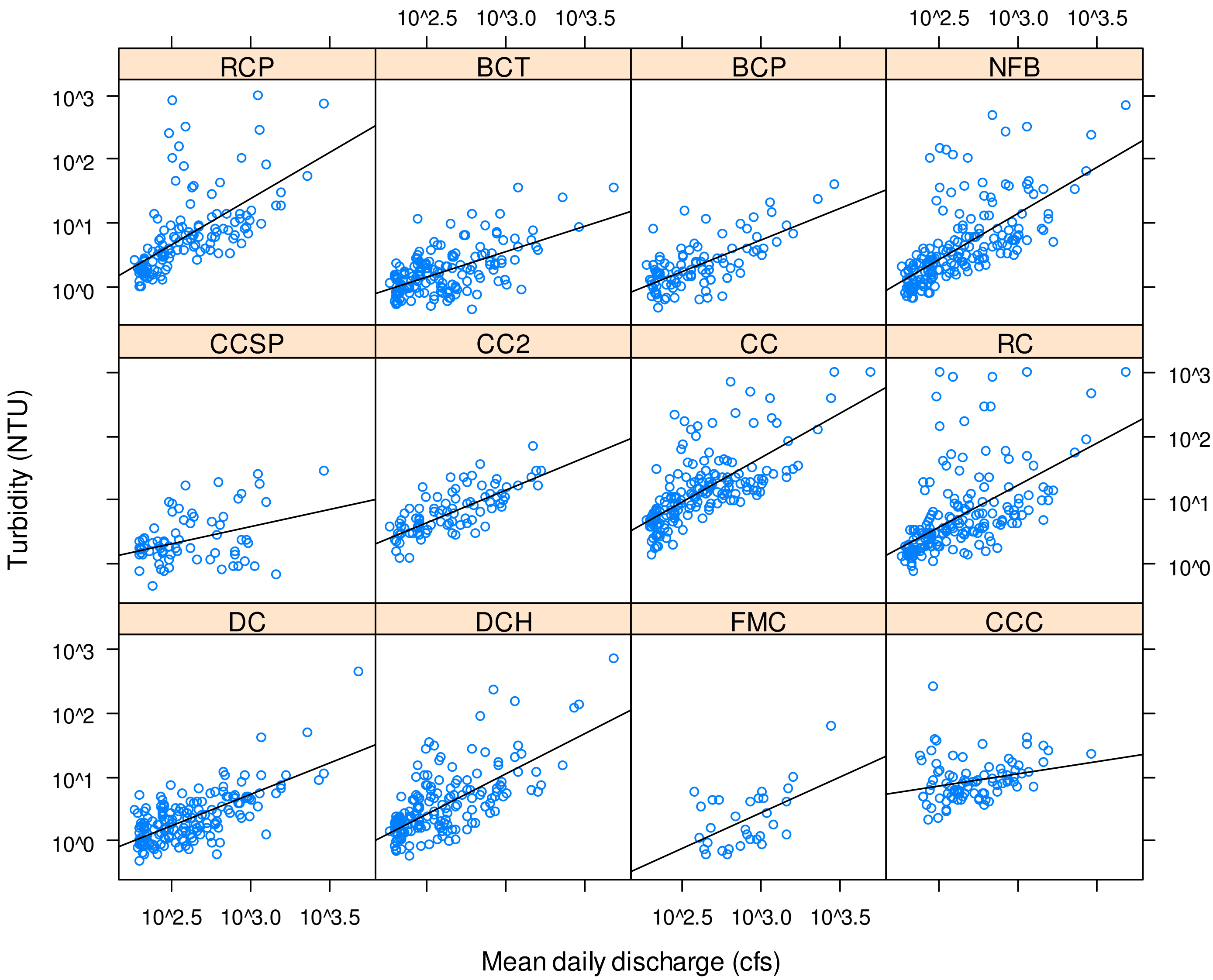

Figure 8. Association of sample turbidity with MDQ.

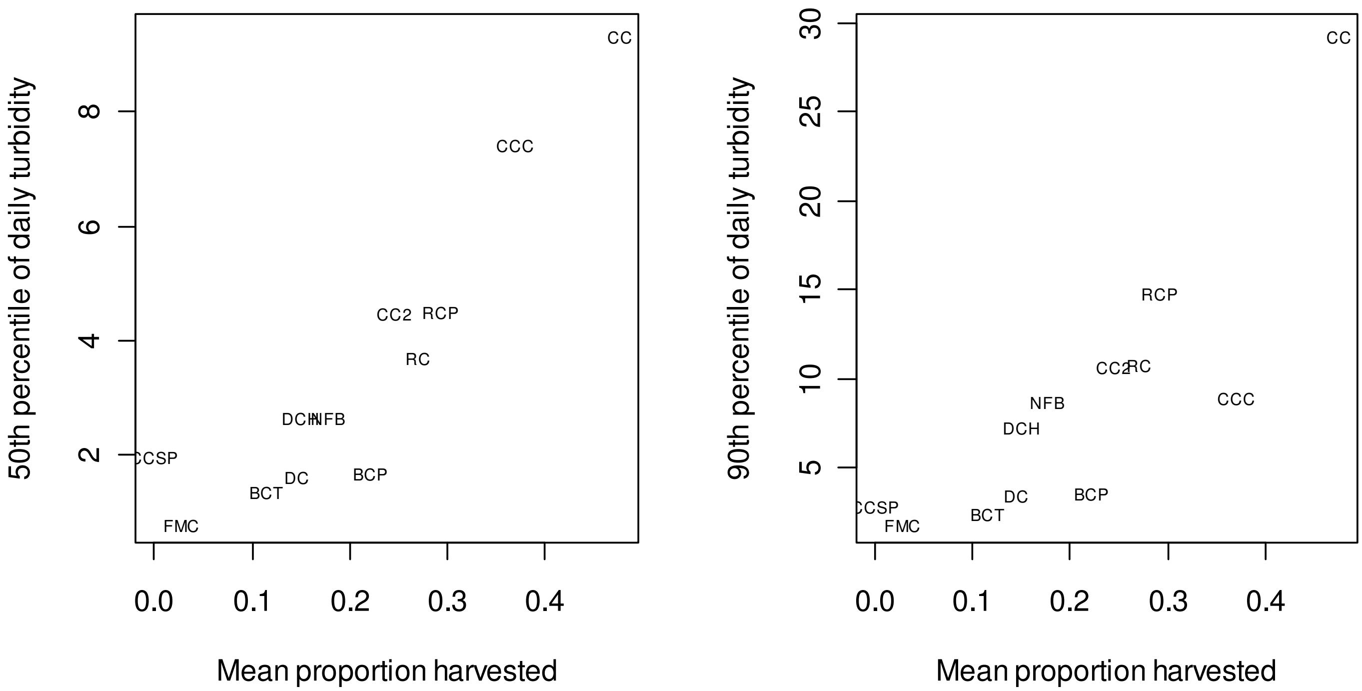

Figure 9. Association of the 50th and 90th percentiles of daily turbidity with mean proportion harvested.

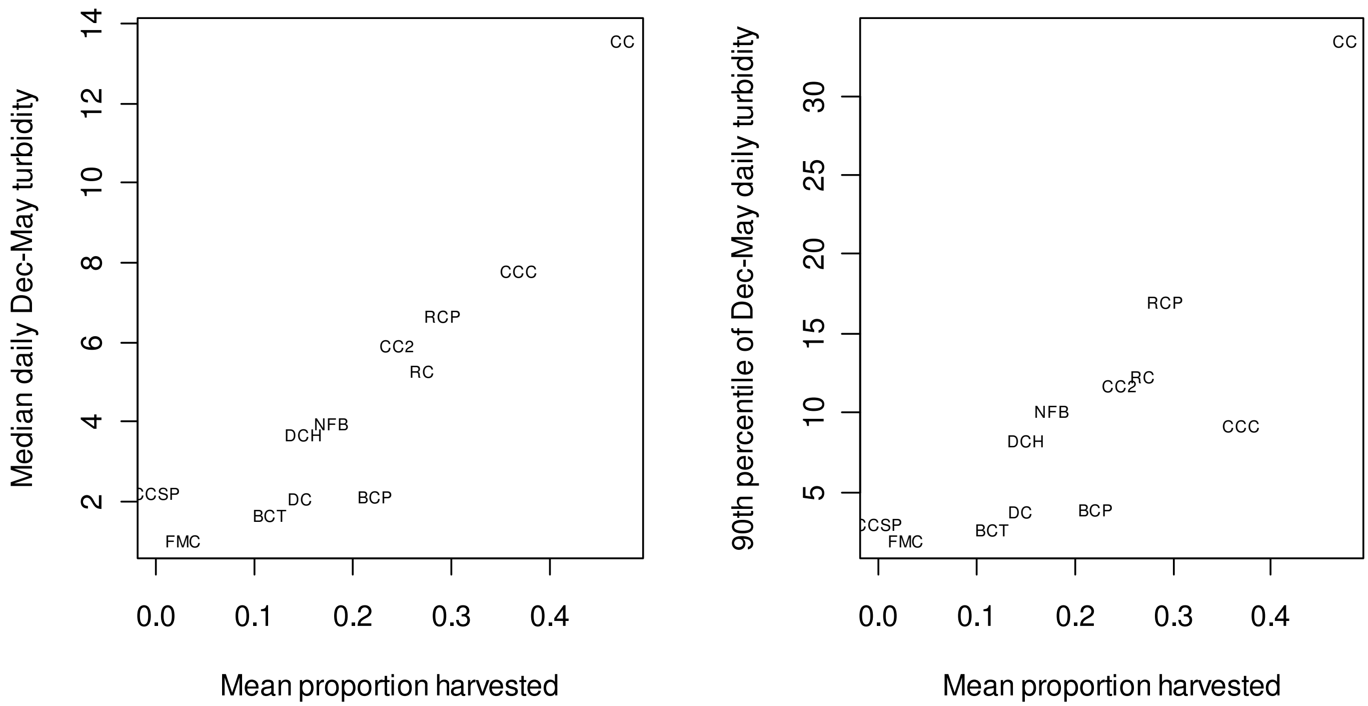

Figure 10. Association of the 50th and 90th percentiles of daily December-to-May turbidity with mean proportion harvested.

Next I fitted a multiple regression model to the individual turbidity measurements (all sites combined) using predictors MDQ, one-day change in MDQ, and proportion harvested. The multiple R^2 for the model is 0.52.

$$\log(T) = -6.53 + 1.36\log(MDQ) - 0.186\log(MDQ1) + 3.79\,pctcut \quad (1)$$

This model does not distinguish among sites because its purpose is to test the effect of harvesting, which would have been confounded with location. All the terms appear to be highly significant (e.g. $p < 10^{-15}$ for proportion harvested) but the observations are not independent and some of the model assumptions are not met (normally distributed errors with equal variance) so the statistical significance is overstated. The signs of the coefficients do make good sense: turbidity is higher for more discharge or cutting, lower if discharge is falling.

The influence of cutting can be visualized by looking at the unexplained portion of turbidity (residual) in a model that accounts only for the discharge variables.

$$\log(T) = -4.73 + 1.41\log(MDQ) - 0.394\log(MDQ1) \quad (2)$$

The residuals are associated positively with the proportion cut at the time of each sample (Figure 11). The right-hand frame of Figure 11 shows the same information, with both variables averaged for each measurement site and we again find a positive association that is statistically significant (Table 6).

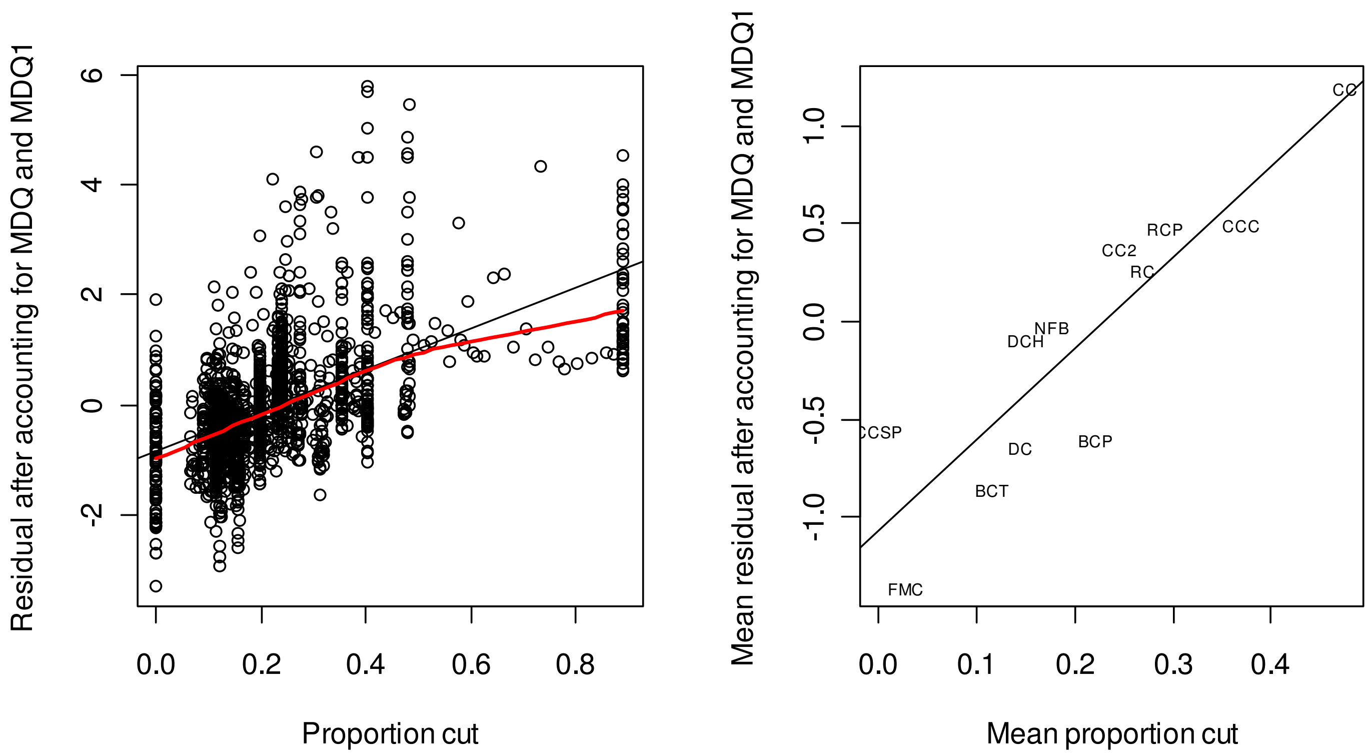

Figure 11. Association of regression residuals from equation (2) with proportions harvested. Regression response is the natural logarithm of turbidity, so vertical axis is in log units to the base e ≈ 2.7183.

How much of the variation in turbidity does harvesting explain? This can be calculated from the coefficient of proportion harvested in the regression model. The value of the coefficient is 3.7938, and the calculation is

$$\Delta T = 2.7183^{3.7938H} - 1$$

where ΔT is the proportional change in turbidity due to harvesting the proportion H of a drainage area. The predicted change varies from 46% for harvesting 10% of a watershed to over 4000% for harvesting 100% (Table 7).

Table 7. Predicted changes in turbidity for a given percentage of a drainage harvested, based on regression model expressing log(turbidity) as a function of MDQ, one-day change in MDQ, and proportion harvested.

% harvested	10	20	30	40	50	60	70	80	90	100
% change in turbidity	46	114	212	356	567	874	1323	1980	2940	4342

Another way we can analyze these data is by testing whether there is a consistent ordering to the turbidity values collected on a given date. Sites CCSP and FMC (as well as SFB) were eliminated in order to obtain a suite of 26 dates with complete measurements at the other 10 sites. All dates in this set precede the Ponderosa fire. The Friedman's rank sum test matches observations by date. The null hypothesis that the sites are equivalent with respect to turbidity is rejected soundly (p-value = 0), indicating that the ordering of the sites at each visit has a consistency, i.e. is not random. For this test, the sites are ranked by turbidity at each visit. Plotting the mean rank against the mean proportion harvested for the measurement dates (Figure 12), we again find a positive and statistically significant correlation (Table 6). As we've seen before the most impacted sites are in Canyon Creek and at RCP.

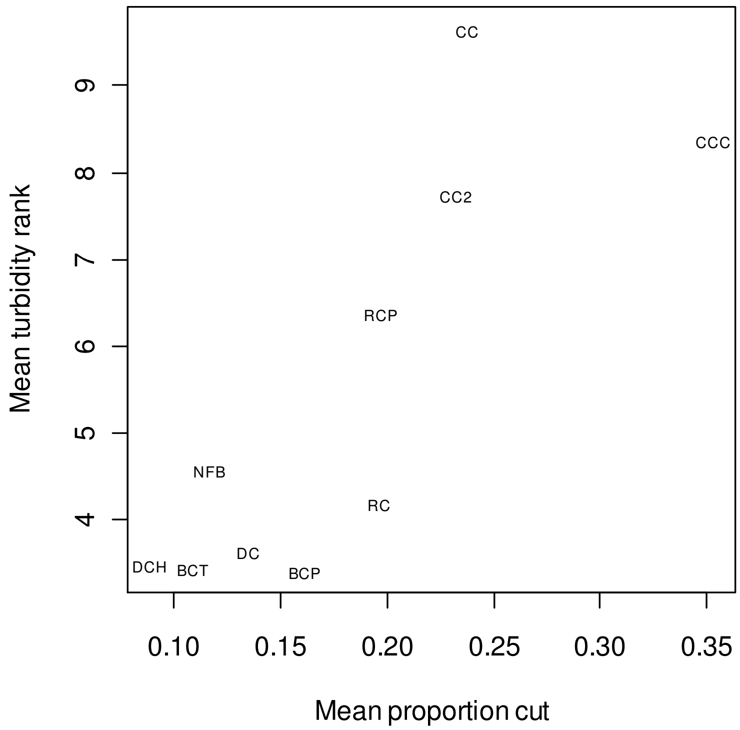

Figure 12. Mean turbidity rank from Friedman rank-sum test in relation to mean proportion harvested for 26 dates that had matched measurements for all sites but CCSP and FMC.

Most of the analyses described so far have primarily been contrasts among sampling sites with different proportions of their drainage areas harvested. If there are confounding variables that are correlated with turbidity and harvest intensity, these could be mistaken for harvest effects. However, we also have a sequence of harvesting in each drainage, so it is possible to look for temporal changes in turbidity at a site (i.e. within-site effects) that could be related to harvesting and/or fire. Such analyses are free of location-related confounding effects such as soil erodibility but may be limited in their usefulness if little harvesting was done during the measurement period. The major logging in some drainages was before BCA began measuring turbidity at the end of 2009. The only harvesting that has been done at the Canyon Creek and Rock Creek sites after 2009 was salvage logging after the fire. Before, the fire in these watersheds one might expect to find either (1) decreasing turbidity, indicating a recovery from earlier harvesting (2) increasing turbidity, indicating delayed harvest effects. After the fire one might see increases in turbidity due to salvage logging, but care must be taken to separate salvage logging from fire effects.

The multiple regression model that was used to generate mean daily turbidity was used to investigate the within-site effects. Trends in the residuals seem small relative to the overall variability (Figure 13), but the

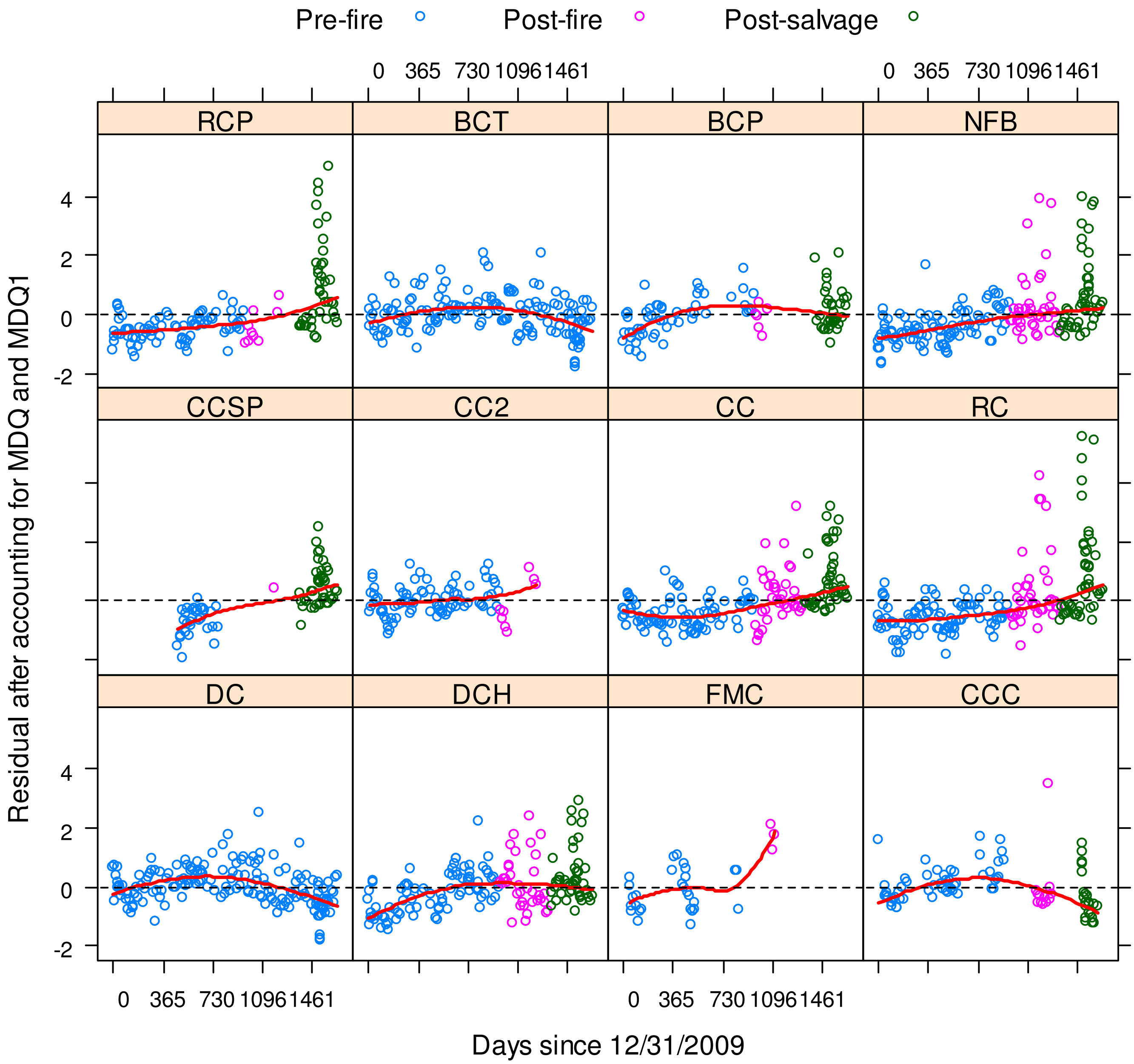

Figure 13. Temporal trends in regression residuals. Symbols identify post-fire and post-salvage periods. Regression response is the natural logarithm of turbidity, so vertical axis is in log units to the base e ≈ 2.7183. Predictor variables in the regression are MDQ and the one-day change in MDQ. A separate MDQ coefficient was estimated for each site.

variability is very great. 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). A value of 2 indicates the turbidity was 7.4 times the predicted value. Among all sites, there are 55 residuals greater than 2 and 53 of these occurred after the Ponderosa fire; 50 of the 55 were at least 6 months after the fires, and 39 were measured in 2014 after salvage logging was completed. Values greater than 2 occurred most frequently at NFB (12), RC (11), CC (9), RCP (8), and DCH (7). Unburned watersheds BCT and DC, had only 1 occurrence each after the fire. CCSP had a very clear increase in turbidity. At CCSP, 29 of 31 residuals greater than 0 occurred after salvage-logging was completed. In terms of turbidity, the majority of post-fire values at CCSP were higher than the *maximum* of 2.31 that was measured before the fire. The burn was not hot enough to kill the larger trees but the ground was disturbed when they were removed from just above the spring as part of the salvage logging. However, only one measurement was made after the fire and before salvage logging, so the two effects cannot be statistically distinguished at CCSP.

Using all sites with drainage areas that were affected by the fire, we can make a contingency table to help separate the effects of the fire from salvage logging (Table 8). The proportion of unusually high residuals (greater than 2) increased from 0.1% before the fire, to 6.4% in the first year after the fires, to 13.9% after one year (post-salvage period). The probability of these proportions changing that much by chance is negligible ($p=10^{-6}$). I proceeded to test each of the five sites listed above that had 7 or more residuals greater than 2 during the measurement period. All tests were significant, and all but DCH were highly so ($p < 0.0015$). These results suggest very strongly that turbidity was elevated much more frequently by the combination of fire and salvage logging than by fire alone. The maximum turbidity measured by BCA in the watershed before the fire was 81 before the summer of 2012. Values between 81 and 1000 have been measured 24 times in the 12 months following the fire and 38 times in the last 10 months of measurements after completion of salvage logging.

Table 8. Contingency tests comparing the occurrence of regression residuals greater than 2 (indicating a value more than 7.4 times the prediction based on discharge) during the pre-fire, post-fire (salvage), and post-salvage periods. Rather than assuming a chi-squared approximate distribution for the test statistic, statistical significance was computed by Monte Carlo simulation (permutation test) with 10^6 replications.

Site		Pre-fire	Post-fire (one year)	Post-salvage	p-value
All but DC and BCT	Residuals > 2	1	12	39	
	Residuals <=2	678	187	280	
	Proportion	**0.0014**	**0.0642**	**0.1393**	**0.000001**
NFB	Residuals > 2	0	4	8	
	Residuals <=2	97	37	37	
	Proportion	**0.0000**	**0.1081**	**0.2162**	**0.0003**
RC	Residuals > 2	0	4	7	
	Residuals <=2	91	37	38	
	Proportion	**0.0000**	**0.1081**	**0.1842**	**0.0014**
CC	Residuals > 2	0	1	8	
	Residuals <=2	88	39	37	
	Proportion	**0.0000**	**0.0256**	**0.2162**	**0.00007**
RCP	Residuals > 2	0	0	8	
	Residuals <=2	77	9	33	
	Proportion	**0.0000**	**0.0000**	**0.2424**	**0.0009**
DCH	Residuals > 2	1	1	5	
	Residuals <=2	84	37	38	
	Proportion	**0.0119**	**0.0270**	**0.1316**	**0.0218**

The trends in Figure 13 are best tested using a non-parametric procedure that does not require normally distributed residuals with equal variance under all conditions. I tested the residuals from each measurement site for monotonic trend using the "adjusted variable" Mann-Kendall test (Alley, 1988) recommended by Helsel and Hirsch (2002). Alley's test is basically a Mann-Kendall test on the partial regression plot of log(turbidity) versus date. In the partial regression plot, log(turbidity) and date are both regressed on the same set of predictors (i.e. MDQ and the one-day change in MDQ), then the two sets of residuals are plotted against one another and tested for monotonic trend using the usual Mann-Kendall test. Since there were 12 sites and 12 trend tests, 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*=0.05/12=0.0042 for each test. Trends were tested for the entire period of record and just the period before the Ponderosa fire (Table 9). Overall trends were significant for all stations but FMC, CCC, CC2, and BCT, with 7 stations increasing and 1 station (DC) declining. SFB, not shown in the table, also increased significantly (p=0.0000). For the pre-fire period, there were no significant declines, while DCH, CCC, BCT, BCP, and NFB all increased significantly. The reduction in the number of significant positive trends may be partly due to the smaller sample size inherent in the shorter period, but it is likely also due to the exclusion of fire and salvage logging effects. Sites DC and BCT are both above the fire area and have been relatively undisturbed since the summer of 2010. Both sites also exhibit a declining pattern of turbidity over the past two years. Site CCC seems to be following a similar trajectory (Figure 13), although it is not statistically significant. An examination of the satellite images in relation to drainage area boundaries indicates that CCC is at the edge of the fire area but was hardly burned at all. Partial tree mortality was observed by BCA in the riparian areas and the larger trees were removed, but this must have been in a small portion of CCC's drainage area. At CC2, the lack of trend is unsurprising because no harvesting has occurred there since sampling began, and sampling was discontinued there shortly after the fire (only 6 post-fire measurements were made). Measurements also were discontinued at FMC because the flow was blocked after alteration of the channel by heavy equipment. Only 3 post-fire measurements were made at FMC, but those measurements strongly suggest an effect from the fire (Figure 13). During the post-fire period, 5 sites (all salvage logged) exhibited significantly increasing turbidity, while 2 sites (both unburned) declined significantly. The post-fire trends (Table 9) strongly support the findings in Table 8, that salvage logging continued to degrade water quality after the fire.

Table 9. Tests for trend in the regression residuals of Figure 13. P-values are from the adjusted-variable Mann-Kendall test. Tests are considered to be significant when $p < 0.0042$ based on Bonferroni correction for multiple testing. Significant increases are highlighted in yellow and significant decreases in gray.

Period	DC	DCH	FMC	CCC	CCSP	CC2	CC	RC	RCP	BCT	BCP	NFB
Whole	0.0000	0.0000	0.0164	0.0641	0.0000	0.4612	0.0000	0.0000	0.0000	0.0329	0.0016	0.0000
Pre-fire	0.0104	0.0011	0.2628	0.0009	0.3232	0.2619	0.5938	0.8666	0.1281	0.0001	0.0000	0.0013
Post-fire	0.0002	0.1680	1.0000	0.3160	0.0037	0.7195	0.0000	0.0000	0.0000	0.0001	0.6202	0.0002

The analysis depicted in Figure 13 and Table 9 can be repeated using proportion harvested in place of day number. This provides a more reliable test of harvesting than a standard t-test of the regression coefficient because of the violated regression assumptions. In addition it provides validation that the trends in Table 9 may actually be related to harvesting. There are clearly some increases in turbidity associated with the fire and salvage logging (Figure 14); these are perhaps most obvious at the Rock Creek sites. The Mann-Kendall procedure finds statistically significant positive associations of turbidity and harvesting at 5 of the sites (Table 10). The negative association at CCC was based on an assumption that the burned portion of the CCC watershed was salvage logged after the fire while turbidity declined. Subsequent inspection of the satellite image indicates that the fire and salvaging in that area was light, so the effect may be an artifact of having overestimated the amount of salvage logging that occurred in CCC. That could also explain why CCC is displaced to the right in Figures 7, 9, 10, and 12. In the pre-fire period, no significant effects were detected (Table 10) because all the watersheds have a nearly constant proportion harvested before the fire. With little or no harvesting having occurred during that period, there is no opportunity to identify an association. All the variation in harvesting is either between sites or post-fire. During the post-fire period, there was a significant positive association of turbidity with harvesting at 4 sites affected by the fire; none of the sites exhibited significant negative associations.

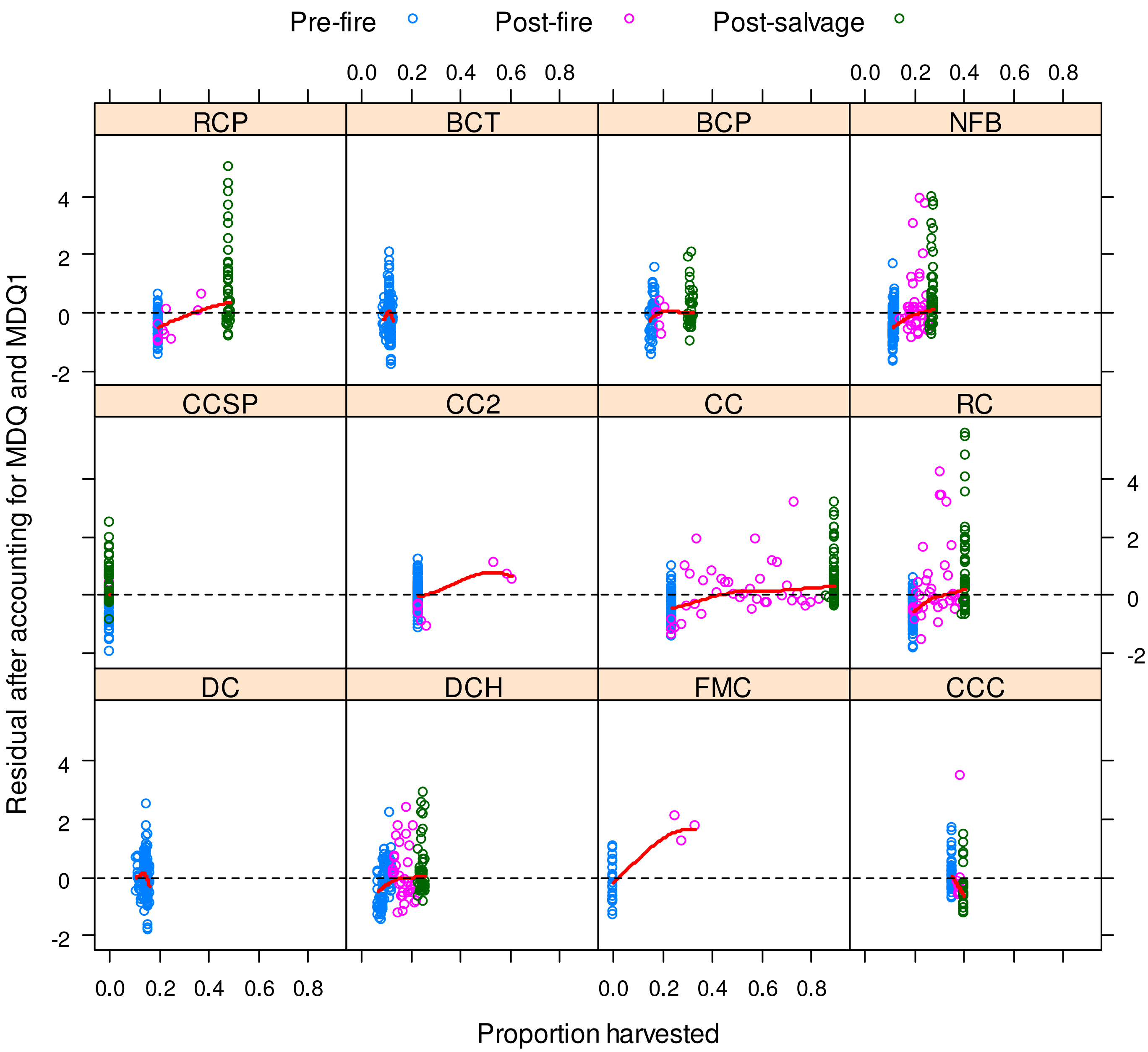

Figure 14. Association of regression residuals with proportions harvested. Symbols identify post-fire and post-salvage periods. These are the same residuals as displayed in Figure 13.

Table 10. Tests of association of regression residuals with proportions harvested using the adjusted-variable Mann-Kendall test. Tests are considered to be significant when $p < 0.0042$ based on Bonferroni correction for multiple testing. Significant increases are highlighted in yellow and significant decreases in gray.

Period	DC	DCH	FMC	CCC	CCSP	CC2	CC	RC	RCP	BCT	BCP	NFB
Whole	0.1339	0.0022	0.5664	0.0038	0.0172	0.7553	0.0000	0.0000	0.0000	0.9790	0.0925	0.0000
Pre-fire	0.2946	0.7499	0.3362	0.2255	0.4020	0.4385	0.0236	0.0290	0.1133	0.0384	0.2429	0.6536
Post-fire	0.0503	0.1631	1.0000	0.5364	0.1747	0.9049	0.0000	0.0000	0.0000	0.0070	0.4504	0.0012

Discussion

Several analyses have shown that turbidity is greatest at those sites whose drainage areas have the highest proportions harvested. Harvesting was positively associated with all percentiles tested from the distributions of sample turbidity, daily turbidity, and December-to-May daily turbidity. In the pre-fire period, sites ranked consistently with respect to turbidity and the rankings were also positively associated with proportions harvested. Regression analysis showed the same effect: after explaining variability in turbidity due to discharge, the remaining variation was related to proportion of watershed harvested. Analysis of regression residuals also showed significant positive temporal trends in turbidity at most of the sites. Sites that did not burn and that have not been logged since 2010 showed signs of recovery, i.e. decreasing turbidity in 2013 and 2014 at DC and BCT. Eight of ten sites that were affected by fire and salvage logging showed significantly increasing turbidity over the monitoring period; one site that was unaffected by fire (DC) decreased significantly. During the pre-fire period turbidity increased significantly at five sites and decreased at none. During the post-fire period, turbidity increased significantly at five sites, while declining at the two unburned sites that had not been recently logged. Five sites that burned each showed a significantly increased frequency of high turbidity values (> 7 times the prediction based on discharge), and their frequency increased most dramatically after salvage logging. Taking all burned sites together, the frequency of these extreme high residuals was 0.1% before the fire, 6.4% after the fire, and 13.9% after salvage logging. A non-parametric test for the effect of harvesting on turbidity at individual sites detected a positive relationship at five sites. Considering only the post-fire measurements, a positive relationship was detected at four sites, all affected by salvage logging.

Overall, it is abundantly clear that turbidity is positively associated with variations in harvesting among sites. There is evidence, within a majority of individual sites, that turbidity is increasing over time and is positively association with harvesting. Finally salvage appears to have turbidity effects above and beyond those of the fire by itself. The statistical findings are based on estimates of when and how much logging occurred. We don't know precisely when salvage logging occurred at each site. Some of these results would likely be even stronger if we had better information about dates and areas harvested.

The North Coast regional study by Klein et al. (2011) found that turbidity was most closely related to the harvest rates in the previous 10-15 years or 0-15 years. The Battle Creek analysis considered the total amount harvested since 1998. No clearcutting had been done before that time in Battle Creek, so the measure of harvesting is similar to the 0-15 year harvest rate in the North Coast study. The importance of the 10-15 year rate in the North Coast study has been attributed in part to delayed landsliding. In Battle Creek, landslides are not an important process, so the 0-15 year harvest rates are probably more relevant. In fact, three subwatersheds that have experienced little or no logging in at least 4 years appear to be on a recovery trajectory. Thus, although the measure of harvesting employed in this study was remarkably well-correlated with turbidity, a shorter window such as 0-5 years might be an even better explanatory variable for future analyses.

This investigation focused on the turbidity data in relation to harvesting. It would be useful to understand and document the causes of elevated turbidity in Battle Creek. A study of erosion sources is not possible without access to privately owned timberlands. However, some of the common erosional processes are visible from county roads in the area. On bare ground that was tractor logged during salvage operations a powdery dirt layer covers the surface. Lacking natural soil structure and herbaceous cover, it is prone to surface rilling by overland flow (Figure 15). When runoff flows onto roadside cut banks, especially in burned areas that have not revegetated, the banks can unravel (Figure 16). Roadside ditches in many places lack armoring and show signs of deepening due to increased surface runoff from compacted and water repellent soils as well as intercepted subsurface flows that are augmented as a result of reduced evapotranspiration.

Other factors that could be influencing the results

Could the turbidity effects be caused by inherent variation in bedrock geology, topography or precipitation? These factors are summarized by Myers (2012). Variation in precipitation and the proportion that falls as snow is primarily a function of elevation, which generally increases to the east towards Lassen Peak. Bailey Creek and Digger Creek originate higher on the mountain than the North Fork, South Fork, Canyon and Rock Creeks. Numerous springs throughout the Battle Creek watershed influence the flows and turbidity. Volcanic flows cover the watershed and andesite is the prevailing bedrock throughout. There are a few small pockets of glacial drift and alluvial soils. Faulting is insignificant. The South Fork is an elongated watershed that has relatively steep slopes along most of its length, but by far the steepest parts of the watershed are at high elevations in Lassen National Park. There are no great contrasts in slope steepness among the North Fork and its tributaries. There are two mapped soil associations in the watershed. The Cohasset-Windy-McCarthy association is mostly north of Digger Creek, and the Jiggs-Lyonsville-Forward association is mostly south of Digger Creek. The soil survey does not distinguish these associations based upon soil erodibility. Overall there are no striking differences in physiographic factors that would easily explain the turbidity differences identified here.

Nevertheless, analyses that contrast harvesting and turbidity among sites (Table 6) could conceivably be confounded by site-specific factors such as those discussed in the previous paragraph. On the other hand, analyses of variation within individual sites (Tables 8, 9, and 10) cannot be confounded by fixed factors such as geology, soils, and topography. Associations of turbidity with time or harvest rate at a site could be influenced to some extent by local variations in precipitation that are not accounted for by MDQ measured at the Coleman station. However such variations are not expected to have a systematic component that would induce multi-year trends. Water diversions throughout the watershed make it so that, even if precipitation were uniform, all acres of the watershed are not equally weighted in the flows measured downstream. We know that flow at the South Fork is highly influenced by PG&E water transfers from the North Fork. But the influences of the myriad diversions for dust abatement, stock watering, fire control, and domestic uses are difficult to quantify or evaluate. The statistical findings could also be influenced by other human activities, but timber harvesting is the primary land use in these watersheds. Domestic, ranching and agricultural uses affect a relatively small part of the land base and recreational activity in the uplands is low-impact.

Figure 15. Surface rilling after salvage logging, September 2014.

Figure 16. Roadcut bank erosion initiated or aggravated by overland flow from harvested areas upslope, September 2014.

Could the results be due to erosion and runoff from roads? Yes, in large part. Many studies have shown that roads are very important sources of sediment in a variety of environments. New or improved roads are included in the harvest acreages documented by THPs; by far most of these roads (634 of 659 acres) are in three THPs in the DCH and SFB drainages. Logging is still in progress in two of these THPs, which opened up and widened existing roads. Since roads are upgraded and trafficked in conjunction with harvesting, it is difficult to separate their effects. Much of the road-related sediment is created by tires abrading the surface particles into fine sediment and dust. This material is subsequently washed into streams during wet conditions. Road traffic during winter operations, commonplace in Battle Creek, aggravates road surface erosion, and can increase rilling and rutting. Reducing the area under THPs would reduce the impact of roads by reducing road maintenance requirements and traffic.

Interagency Task Force Report

The Interagency Task Force (ITF) report (CALFIRE et al., 2011) on Battle Creek has been cited in recent THPs to suggest that there are no significant direct water quality impacts in Battle Creek related to clearcut harvesting. Such interpretations are inappropriate as a lack of evidence of impacts using the ITF rapid assessment methodology does not constitute evidence of no impacts. The purpose of the ITF report was to determine whether observable water quality impacts are originating from clearcut areas, but due to the short time frame required for the report no water quality data were actually collected. The rapid assessment methodology is a blunt tool for assessing water quality impacts from typical erosion processes in the area. To its credit, the ITF clearly stated that they "would not be able to directly assess all potential mechanisms of sediment delivery, such as potential increases in suspended sediment and turbidity associated with harvest-related increases in peak flows." The report acknowledges that "Clearcut logging does have the potential to increase rates of road erosion below a harvest unit (La Marche and Lettenmaier, 2001), due to increased runoff intercepted by road cutslopes. However, this cause-and-effect mechanism could not be evaluated using a rapid assessment methodology." And while the ITF reported only one instance of direct sediment delivery from harvest areas, it does acknowledge the linkage between timber harvest and sediment delivery from other related disturbances. "Although tractor crossings, road crossings, and watercourse-adjacent road segments had the highest risk of delivering sediment to watercourses, these features are associated with all forms of timber harvest, including selection harvesting."

Why didn't the ITF identify more direct sediment delivery from harvest areas and watercourse-adjacent landings? For several reasons, evidence of erosion and sediment delivery from harvest areas may have been difficult to observe:

1. Observations were made in September, at the end of the dry season.
2. The prior winter (2011) had been a below average rainfall year.
3. Small rills (the dominant form of erosion), whether on roads or harvested surfaces, fill in with time.
4. Prior surface erosion may be hidden by regrowth of herbaceous vegetation and leaf fall, or wood-chip mulches applied to protect landing surfaces.
5. Large erosion voids typically associated with mass wasting are rare in the relatively subdued topography and volcanic soils that comprise Battle Creek.
6. Estimating volumes delivered from sheet and rill erosion is virtually impossible even if those sources can be identified.

The ITF did report "ample evidence of sedimentation from bank erosion within the assessment area"; however its importance was dismissed because much of it appeared to have been associated with a large 1997 storm event. Bank erosion was thus identified as an important process in Battle Creek and if an event like the 1997 storm occurs before substantial regrowth after clearcutting, the unavoidably increased flows will have an even greater impact. The report states that "the issue of timber-harvest-induced changes in hydrology in ground-water dominated, young volcanic terrains such as Battle Creek watershed remains an open question." But trees still intercept and transpire water, and there will be excess soil water wherever they are removed. Although some portion may enter deep storage, the excess water has ample opportunity to emerge wherever groundwater already surfaces throughout the watershed, including natural springs as well as roadcuts and inboard ditches.

The ITF report was based on observations taken before the Ponderosa fire and subsequent salvage logging. Prior to the fire, the BCA data indicate relatively small turbidity increases in Battle Creek, although they were statistically significant in Digger Creek (DCH), Canyon Creek (CCC), Bailey Creek (both sites) and NF Battle Creek (Table 9). Figure 13 and Table 8 of this report show that the biggest changes in turbidity occurred after the fire and subsequent salvage logging. An assessment of sediment delivery and erosion could not be undertaken without permission from SPI, hence was beyond the scope of this study. Nevertheless, limited post-salvage field observations (Figures 15 and 16) show obvious evidence of erosion and sediment delivery associated with harvest areas. Two years after the fire, very little regrowth has taken place in areas that were salvage logged (Figures 2, 15, 16); exposed soils are widespread and remain at high risk for erosion.

Conclusion

Battle Creek contains important cold-water habitat for threatened and endangered runs of Chinook Salmon in the Sacramento River system. In the past 15 years, clearcutting has been introduced to the Battle Creek watershed and timberlands have been very heavily harvested: about 48% of industrial holdings in the North Fork (NFB drainage) and 18% in the South Fork (SFB drainage). In the Ponderosa fire area at least 17,000 acres have been largely denuded by clearcutting followed by fire in 2012 and subsequent salvage logging. At the end of 2009, the Battle Creek Alliance began measuring turbidity at 13 locations in the watershed. As of July 2014, 1680 measurements had been recorded. Statistical analyses of these measurements demonstrate strong associations of turbidity with the proportion of area harvested in watersheds draining to the measurement sites. In all analyses, the sites with the most harvesting (especially Canyon Creek and Rock Creek) have the highest turbidity. In addition there are statistically significant increasing turbidity trends at individual sites and these trends are related to harvesting. Turbidity increased over the measurement period at a majority of sites, during the pre-fire period at five sites, and during the post-fire period (reflecting the influence of salvage logging) at five sites. There is good evidence that salvage logging affected turbidity above and beyond effects of the fire alone. Extreme turbidity measurements more than 7 times the average value for a given flow condition were almost non-existent before the fire but began to appear after the fire (6% of measurements) and have become fairly common (14% of measurements) since salvage logging was completed. Turbidity has decreased only recently at upper Digger Creek and upper Bailey Creek, whose catchments were unaffected by the fire and have not been harvested in the past four years. The average change in turbidity for a watershed that has been 30% cut is +200% and, for a watershed that has been 90% cut it is 3000%. These changes, which are far in excess of the Water Board's Turbidity Standard for the Central Valley region (see Addendum below), are unlikely to have been caused by factors other than harvesting, fire, salvage logging, and associated road use. Since continuous turbidity measurements were not available for this analysis, the durations of elevated turbidity in relation to ill effects on salmonids after salvage logging are unknown. However, SPI has been collecting such data at three locations in the watershed (James and MacDonald, 2012) since 2002 and at three other locations since 2011. Because of their relevance to critical fisheries and restoration efforts in Battle Creek, it is important that these continuous turbidity data be analyzed and released to the public.

Addendum: Central Valley Basin Plan Turbidity Standard

Waters shall be free of changes in turbidity that cause nuisance or adversely affect beneficial uses. Increases in turbidity attributable to controllable water quality factors shall not exceed the following limits:

- Where natural turbidity is less than 1 Nephelometric Turbidity Unit (NTU), controllable factors shall not cause downstream turbidity to exceed 2
- Where natural turbidity is between 1 and 5 NTUs, increases shall not exceed 1 NTU.
- Where natural turbidity is between 5 and 50 NTUs, increases shall not exceed 20 percent.
- Where natural turbidity is between 50 and 100 NTUs, increases shall not exceed 10 NTUs.
- Where natural turbidity is greater than 100 NTUs, increases shall not exceed 10 percent.

In determining compliance with the above limits, appropriate averaging periods may be applied provided that beneficial uses will be fully protected.

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