An Analysis of Water Temperature and the Influences of Wildfire and Salvage Logging in the Battle Creek Watershed, northern California

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Prepared for the

Battle Creek Alliance, Manton, CA

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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. Detailed descriptions of the climate, soils, geology, topography, vegetation, stream morphology and aquatic conditions can be found in reports by Kier Associates (2009) and Myers (2012). Battle Creek is a drought-resistant, spring-fed system that is important to anadromous fish 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 migration barriers and 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 (BCRP) is in the process of restoring about 48 miles of habitat through modification of hydroelectric project facilities, operations, and management.

Water temperature is an important factor in behavior and function of all life stages of anadromous fish, affecting (for example) disease resistance and successful reproduction, incubation, rearing, migration, feeding, and competition. In Battle Creek, temperature is influenced by groundwater, meteorological conditions, stream morphology, riparian canopy, water diversions, and flow releases below diversion dams. Warm water temperatures may limit habitat quality particularly during the summer months of June–September (Kier Associates 1999). Water temperatures during October–May are cool and generally have minimal effect on survival (USBR AND SWRCB, 2005).

The Battle Creek Alliance (BCA) began measuring turbidity, water temperature and pH at 13 locations in the watershed in December 2009. Lewis (2014) analyzed the turbidity data collected through July 3, 2014 and found that turbidity was elevated in association with (1) clearcutting, (2) the Ponderosa wildfire of 2012, and (3) post-fire salvage logging. This report summarizes new analyses that focus on changes in water temperature and some of their influences.

Influences on riparian canopy

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 August 2012 satellite image (Figs. 1 and 2) 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 (Fig. 3), most of which was salvage logged in the following year (Fig. 4).

California Forest Practice Rules (FPRs) address timber operations in Water and Lake Protection Zones (WLPZ) for protection of water quality (including temperature) and aquatic and riparian species and ecological functions. The width of the WLPZ varies from 50 to 150ft, depending on slope steepness, watercourse class, and other factors. The WLPZ rules provide shade to the stream primarily as a function of two rules: (1) in Class I (fish-bearing) streams, at least 50% of the overstory and 50% of the understory canopy must be retained, and (2) in Class II streams, i.e. reaches no more than 1000 feet upstream from fish-bearing reaches or streams with aquatic habitat for non-fish species, at least 50% of the total canopy must be retained. Class III streams, i.e. those capable of sediment transport but with no aquatic life present, are only protected from removal of understory vegetation, hence are not well-protected from the loss of shade. As the FPRs pertain to the study area, salvage logging of dead or dying conifers is permitted under emergency rules within the WLPZ except in "Core Zones" within 30 feet of Class I streams or within 20 feet of "large" Class II streams.

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 on the North and South Forks of Battle Creek (Table 1, Fig. 1). All sites except SFB have, in recent history, been inaccessible to anadromous salmonids due to the fish barrier at Eagle Canyon Dam. Drainage areas in Table 1 are based upon surface topography, but may not be very well-related to flows 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.

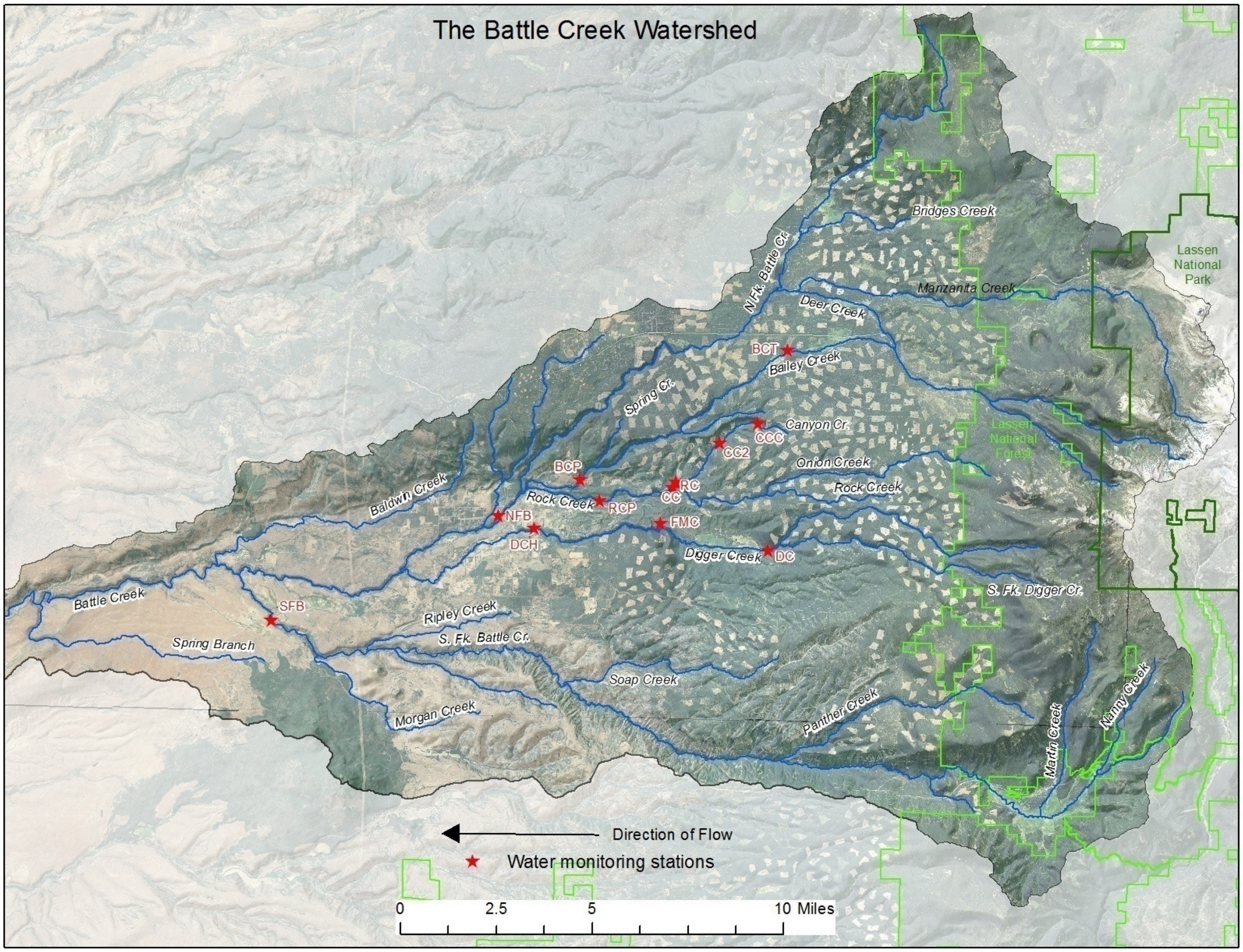

Figure 1. Battle Creek watershed and BCA sampling sites. Checkered appearance is due to clearcutting. Image was taken prior to the 2012 Ponderosa fire, hence does not include salvage logging and more recent harvesting.

Table 1. BCA sampling sites and characteristics

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

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. Sites NFB and SFB are the only monitoring sites affected by the PG&E diversions. From Water Diversion Statements and Licensee Reports, 2009-2015, I calculated that an average of 67,250 acre feet is diverted annually from the North Fork to the South Fork above site SFB. This has enhanced the mean annual flow at SFB by 55%, but diversions have declined since 2012 (Fig. 5). Of the total diverted flow, an average of 45,355 acre feet had been withdrawn from above site NFB in 2009-2015, or about 31% of the annual flow at that site. (Annual flows at NFB and SFB are estimated very roughly, based on watershed areas relative to the gage at Coleman Fish Hatchery).

Water is also exported from the South Fork above site SFB via the Coleman Canal, which conveys this water to the Coleman Powerhouse and discharges to the mainstem of Battle Creek. In 2012, as part of the BCRP, a tailrace connector and penstock bypass system were constructed to convey North Fork water from the Inskip Powerhouse into the Coleman Canal to keep it from mixing with South Fork streamflows, but this is not yet in service. By 2020, the Restoration Plan specifies that, to guard against false attraction of anadromous fish away from their migratory destinations, no North Fork flows will be conveyed into the South Fork. Water diversions from North Fork to South Fork Battle Creek tend to warm the North Fork Battle Creek by removing its cool water and to cool the South Fork Battle Creek by introducing relatively cold water at South and Inskip Powerhouses (USBR AND SWRCB, 2005). For the period of this analysis, measurements at SFB still reflect, to a significant extent, transfers from the NFB watershed.

The percentages clearcut in Table 2 are values estimated by Lewis (2014) using Google imagery but have been revised slightly using the latest available Google Earth image (May 27, 2014) for the study area. It is also assumed that the Reynolds THP (2-12-026 SHA), which was in progress in the Bailey Creek watershed in 2014, was completed by mid-November of that year. The 2012 Ponderosa Fire killed nearly all of the merchantable-size trees (Fig. 3) and nearly all were salvage logged within a year (Fig. 4). The assumed completion date for salvage logging is August 31, 2013. The salvage logged area was calculated for each drainage as the total acreage within the fire boundary, subtracting previously harvested areas, and unsalvaged areas that could be delineated. Watershed boundaries, elevations, areas draining to each sampling site, and measures of disturbance (Tables 1 and 2) were derived with the GIS assistance Curtis Bradley (Center for Biological Diversity).

Table 2. BCA sampling sites and some measures of disturbance.

Site ID	Name	Percent clearcut (including salvage)	Percent burned	Percent salvage logged	Percent of burned area salvage logged	Percent of NHD flowlines salvage logged
BCT	Bailey Creek upper	13.1	0.0	0.0	not applicable	0.0
BCP	Bailey Cr lower	33.9	13.8	11.1	80.3	5.8
CCC	Canyon Cr upper	57.7	48.0	22.4	46.8	18.3
CCSP	Canyon Cr spring	0.0	100.0	NA	NA	NA
CC2	Canyon Cr middle	82.0	83.6	58.8	70.4	15.9
CC	Canyon Cr lower	88.0	90.8	64.2	70.7	33.0
RC	Rock Cr upper	38.4	28.7	18.8	65.4	25.4
RCP	Rock Cr lower	46.8	39.3	27.1	69.0	27.6
DC	Digger Cr upper	15.7	1.0	0.5	50.4	0.0
FMC	Digger Cr trib	100.0	100.0	100.0	100.0	not applicable
DCH	Digger Cr lower	27.1	18.5	14.1	76.4	14.1
NFB	North Fork Battle	28.1	9.6	7.0	72.6	7.5
SFB	South Fork Battle	19.2	19.0	13.3	assumed 70%	not estimated

Field Methods

The measurement period analyzed in this report is from Dec. 30, 2009 to May 18, 2016. Water temperature was initially measured in situ at each field visit with a Hanna pH and temperature meter, Model HI 98121. Beginning Nov. 6, 2011 temperature was measured with a pool thermometer. The two instruments agree to within 1°C. About two cups of stream water were sampled and the measurement was recorded after two minutes to allow the thermometer temperature to stabilize. 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.

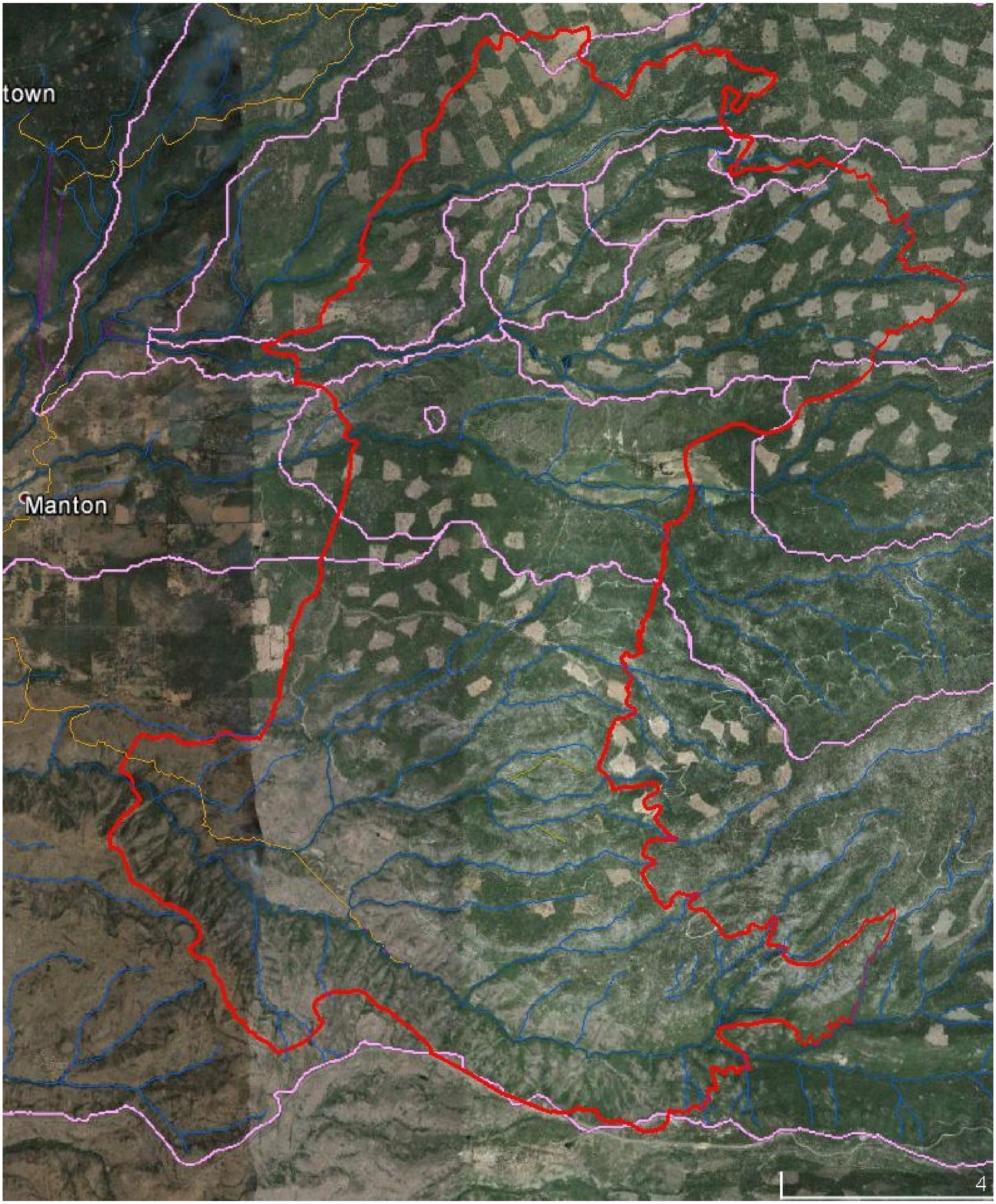

Figure 2. Google Earth composite image immediately before the 2012 Ponderosa fire (Aug 18, 2012). Fire boundary is shown in red, watershed boundaries in pink, and streams in blue.

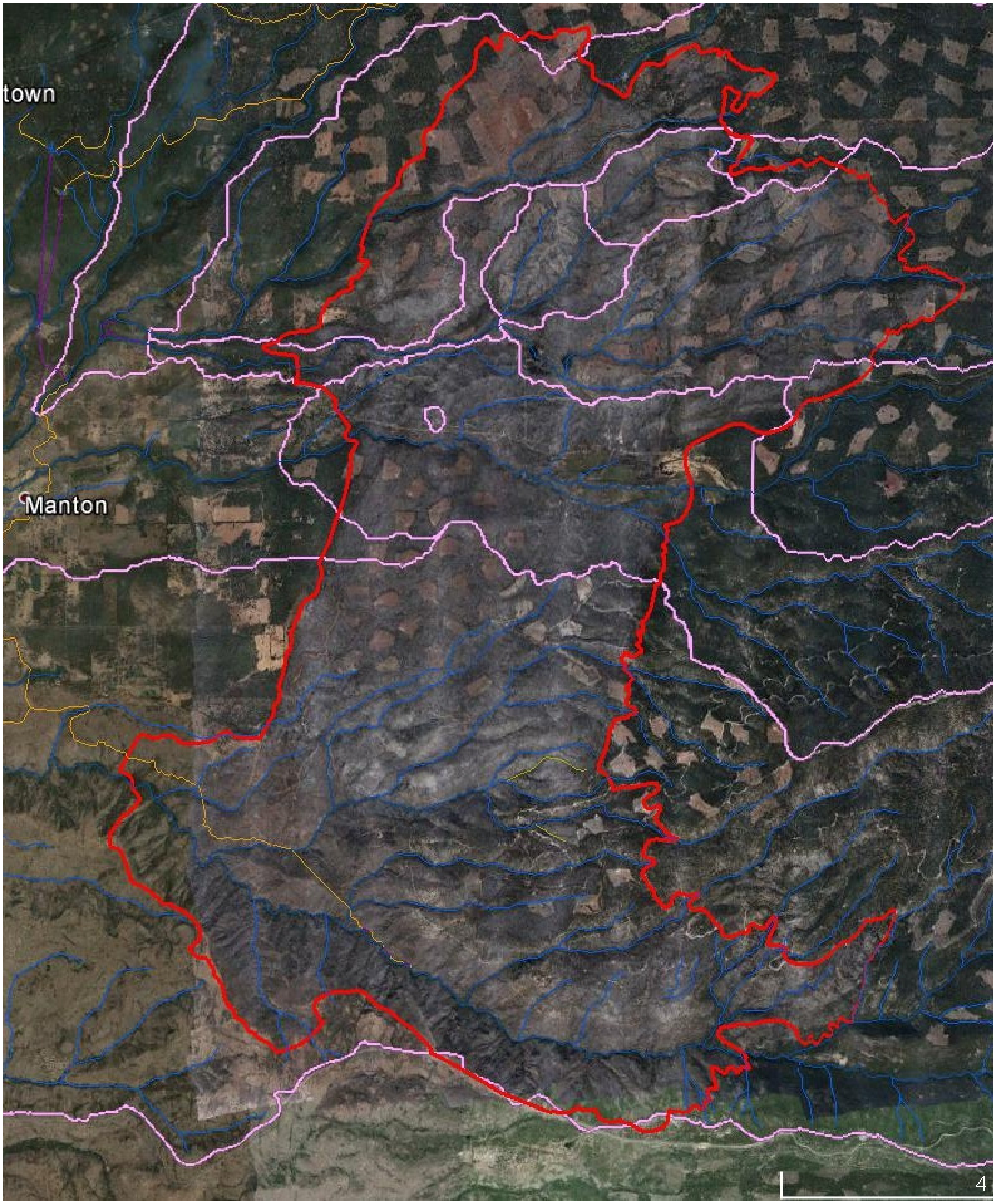

Figure 3. Google Earth composite image shortly after the 2012 Ponderosa fire (Sep 23, 2012).

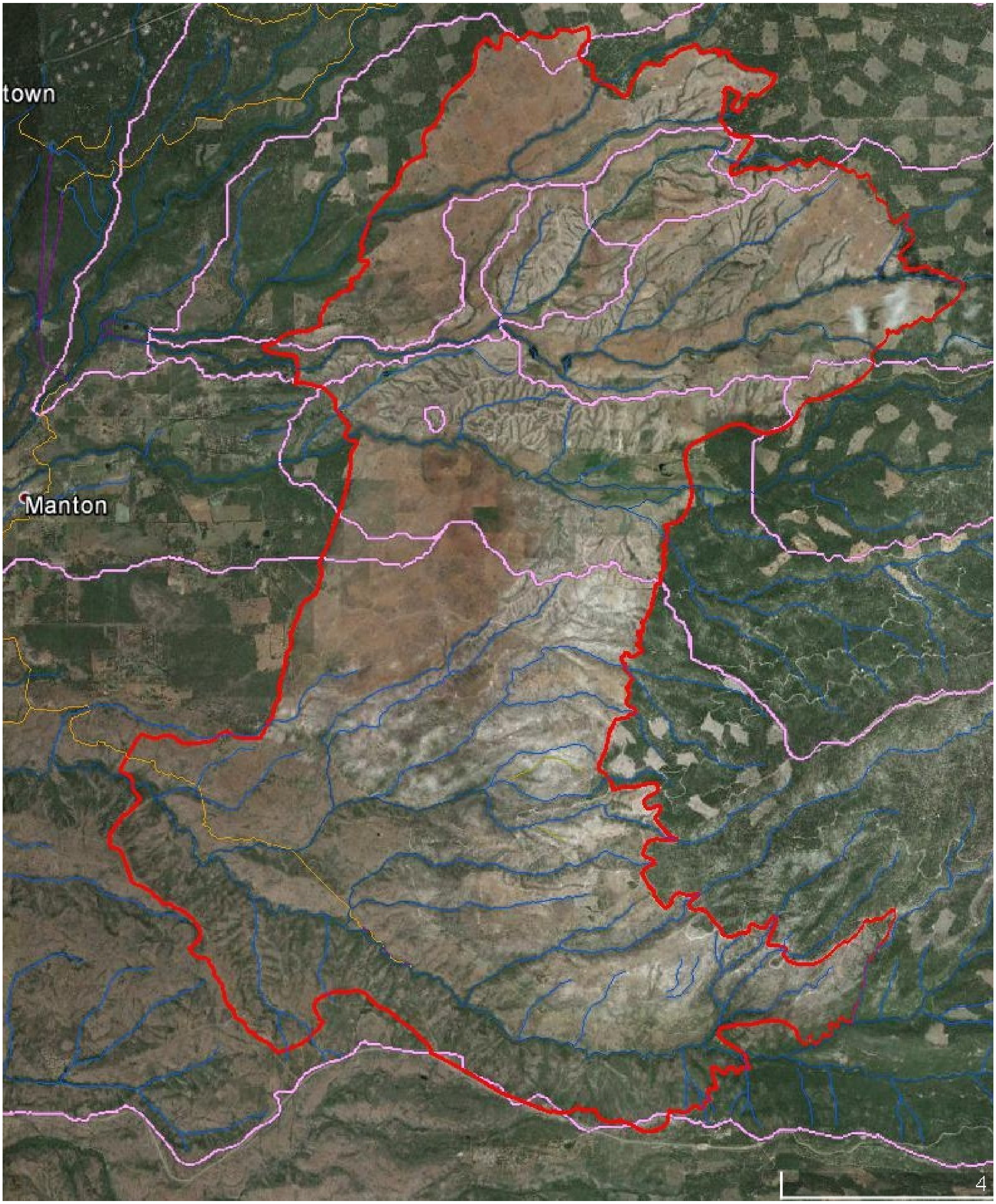

Figure 4. Google Earth composite image after salvage logging and herbicide application (May 27, 2014).

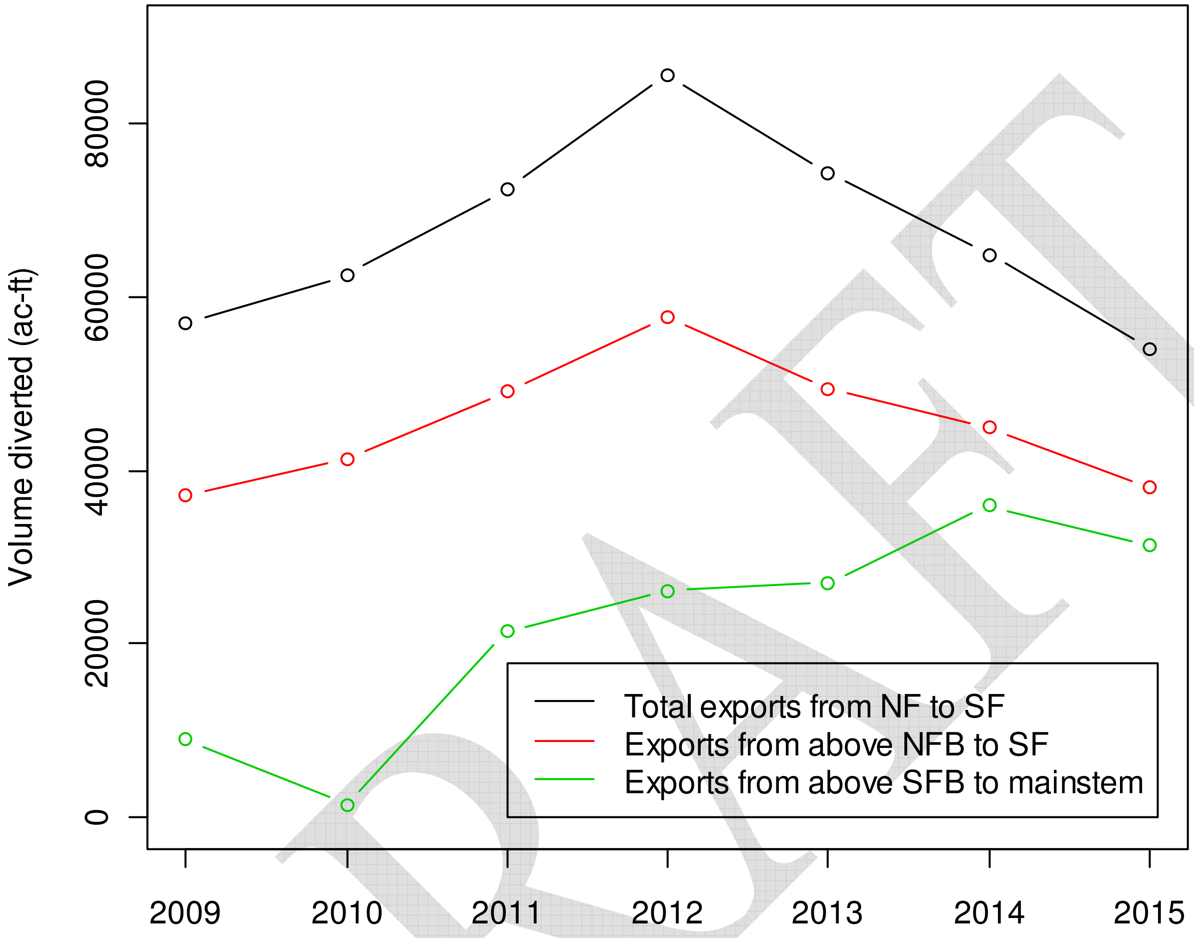

Figure 5. Summary of diversions between the North and South Forks and mainstem of Battle Creek

Data Validation

The U.S. Fish and Wildlife Service (FWS) also monitors water temperatures in the Battle Creek Watershed. They use calibrated Onset Hobo model U22-001 data loggers, which according to the manufacturer are accurate to within ±0.21°C from 0° to 50°C and are stable to 0.1°C/yr. The loggers are deployed inside PVC casings that sink to the bottom of the creek and are attached to metal cables affixed to trees on the bank. Temperatures are recorded at 30-minute intervals. Most of the BCA sites are on tributaries that are not monitored by FWS, but there are two exceptions: FWS sites 16 and 17 are located a few hundred feet apart near the Volta Powerhouse approximately 0.7km upstream from BCA site NFB, and FWS site 19 is at the Manton Bridge, the same location as BCA site SFB. Site 17 wasn't installed until May 2014, so FWS data at only sites 16 and 19 were interpolated to the BCA measurement times at sites NFB and SFB in order to validate the BCA data. Some of the analyses performed on the BCA data were also carried out on FWS sites 16 and 19 for comparison.

Statistical Methods

Regression modeling and trend testing

A regression model was fit to account for the variability associated with daily swings in air temperature. Air temperatures were obtained from the National Climatic Data Center for the nearest hourly weather station, Redding Municipal Airport. The hourly air temperatures were interpolated to the times of each water temperature measurement. Although Redding airport is 37km west of the NFB monitoring site and 475m lower, the air temperatures are well-correlated with water temperatures at all the stream monitoring sites. However, departures from a simple regression model are systematically greater in the summer, even after including discharge in the model, so adding a quadratic term for time of year improves the model significantly, and raises the multiple R^2 from 0.78 to 0.85. The following multiple regression model was adopted

$$WT_i = \beta_{0,i} + \beta_{1,i} AT + \beta_{2,i} D + \beta_{3,i} D^2 + \beta_{4,i} \log(MDQ) \tag{1}$$

where WT_i is the water temperature at site i, AT is the Redding air temperature, D is day number counting from Jan 1, and MDQ is mean daily discharge at the Coleman Fish Hatchery downstream on Battle Creek. All sites were combined in computation of the regression but separate intercepts and coefficients were estimated for each sampling site i, so the model is equivalent to 13 separate regression models. The residual standard error for model (1) is 1.9°C.

To investigate changes in water temperature, residuals were plotted against time and tested for monotonic trends using the adjusted Mann-Kendall trend test (Alley 1988), recommended by Helsel and Hirsch (2002). The Bonferroni adjustment was used to control for simultaneous testing of up to 13 sites, so tests were considered significant only when $p < 0.05/n$, where n = the number of sites tested. Residuals were compared year by year for burned and unburned watersheds. Trends and comparisons were repeated for data collected in only the pre-fire, post-fire, and post-salvage periods, and for measurements made during only the hottest months: June to September. Results are interpreted as suggestive of the effects of wildfire and forest management after accounting for variations in air temperature, general flow conditions, and time of year.

The Ponderosa Fire started on Aug. 18, 2012. After containment on Aug. 31, 2012, efforts were made to quickly salvage log all remaining burned trees over 30cm in diameter at breast height. The exact timing of the salvage logging has not been publicized, but it is thought to have been completed in well under one year. For the purposes of analysis, I have assumed that all salvage logging occurred within the first year after the fire was contained. Early measurements during that period reflect primarily the influence of fire, while later measurements reflect progressively increasing influences from salvage logging. The post-salvage period, starting Sep 1, 2013 reflects the full effects of both salvage logging and wildfire.

Digger Creek upstream-downstream analysis

Digger Creek has two gaging sites: DC with a catchment area of 55 km^2 and DCH with an area of 91 km^2. DCH is approximately 8 km downstream of DC and the watershed between the two sites was almost entirely burned and salvage logged down to the stream channels. Prior to the monitoring period approximately 7.2% of DC had been clearcut and another 7.0% was cut in the first several months of the monitoring period. These harvests amounted to about 9% of the DCH watershed and another 3.5% of the DCH watershed was harvested in the summer and fall of 2011. The Ponderosa Fire came through in late August 2012. Only 1% of the DC catchment was affected by the Ponderosa fire, compared with 18.5% of the DCH watershed. After the fire, about 0.5% of DC's watershed and 14.1% of the DCH watershed was salvage logged. Thus we can track the impacts of logging in 2011 and the fire and salvage logging by comparing water temperatures at these two sites. Temperature was always measured at both sites on the same day during site visits; 81% of measurements were within 1 hour of each other, 95% within 2 hours, and 100% within 4 hours. The daily pairs were plotted and the relationships between the two sites were compared for the three different monitoring periods to evaluate the influences of logging, fire and subsequent salvage logging.

Estimating maximum daily water temperatures

In order to evaluate temperature stresses on Chinook and steelhead populations, I estimated hourly water temperatures, applying the *composite* method of Aulenbach and Hooper (2006) with regression expression (1) and plugging in the hourly Redding air temperatures, mean daily discharge at the Coleman hatchery, and month of the year. Separate regression coefficients were computed before and after the Ponderosa fire. Without applying the composite method, the pre-fire and post-fire predictions would reflect static conditions modeled during each period. The composite method applies a residuals-correction. Residuals are interpolated through time and added back to the regression predictions to give results that reflect a sequence of temperature changes in the riparian zone, not just average conditions before and after the fire. The modeled series could potentially reflect growth in the riparian zones, fire effects, salvage logging, water diversions, and any other influences on water temperature. The maximum daily water temperatures were extracted from the hourly series and the maximum weekly maximum temperature (MWMT) was computed for comparison with published thresholds. MWMT is the maximum annual value of a 7-day running mean of daily maxima; it is considered a measure of both chronic and acute affects (Carter, 2005).

RESULTS

Data validation

Temperatures measured at the BCA sites are systematically higher than those measured at the nearest FWS site (Fig. 6), and, judging from the agreement between FWS sites 16 and 17, they have lower precision. Possible sources of the systematic bias are (1) the measurement instruments, (2) BCA measurements are made in the air, while the FWS Hobos are deployed in situ, (3) BCA samples are collected from near the surface while the Hobo loggers are housed in PVC pipes on the channel bed. Possible sources of the difference in precision are (1) and (2) above, and human error in reading and recording. If the temperature differences were constant, as Fig. 6 suggests at first glance, then the BCA temperatures could be adjusted using this data set, in order to be more comparable to published thermal tolerances for salmonids. However, the independent variable would have to be the BCA temperature, and a closer look at the differences indicates that the pattern of bias is different at sites NFB and SFB (Fig. 7, left two frames). Differences at NFB depend strongly on temperature while those at SFB are nearly independent of temperature. There are no data that would permit a determination of whether either relationship applies to the other 11 BCA sites.

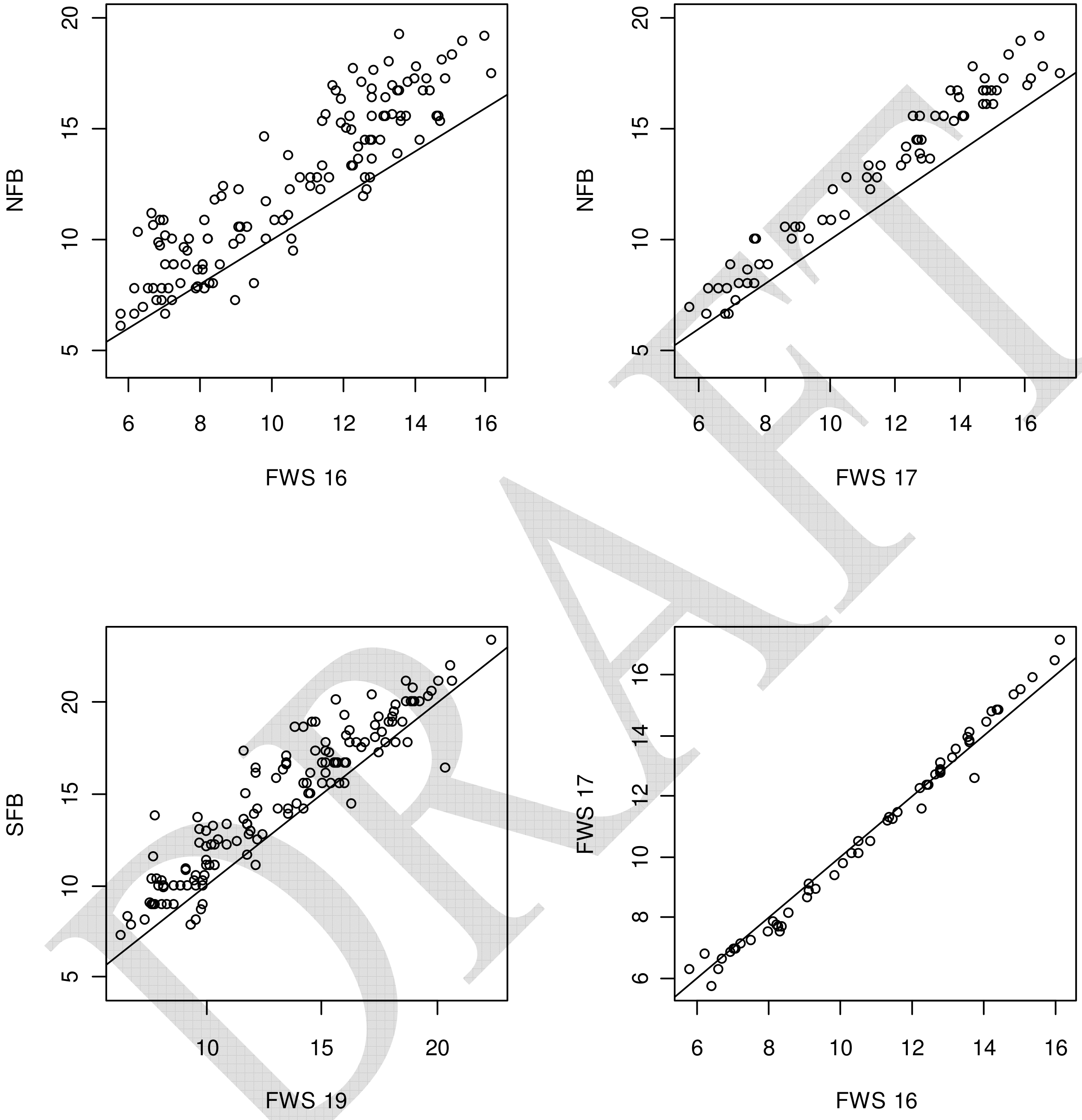

Figure 6. Temperatures in degrees Centigrade, comparing BCA and FWS measurements on the North Fork (NFB, FWS 16, FWS 17) and South Fork (SFB, FWS 19) Battle Creek. The diagonal line in each plot represents the 1:1 relationship (y=x).

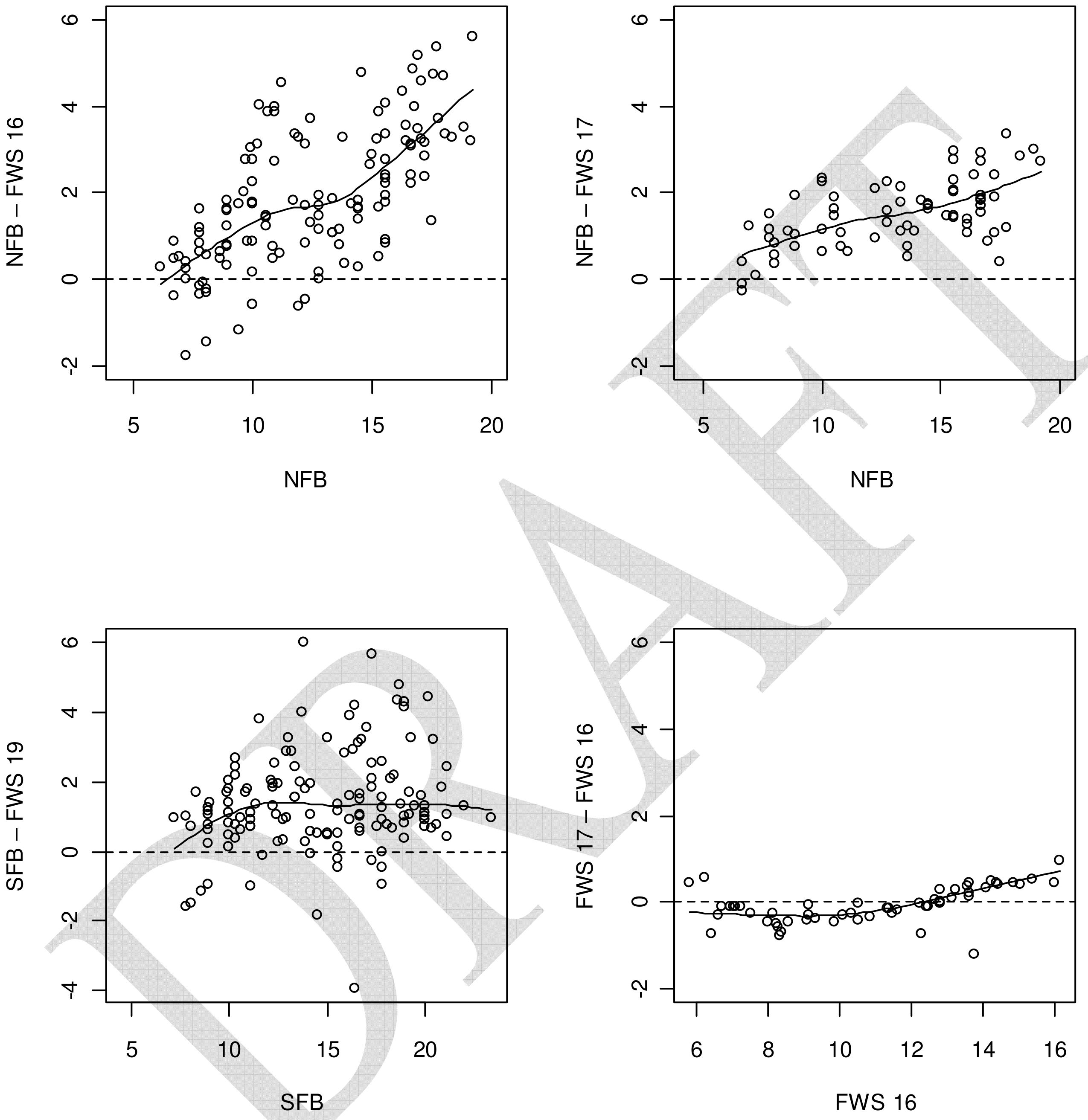

Figure 7. Temperature differences in degrees Centigrade, between BCA and FWS measurements on the North Fork (NFB, FWS16, FWS17) and South Fork (SFB, FWS19) Battle Creek. Curves are fitted using loess (Cleveland and Devlin, 1988).

Trends in regression residuals

Year-round temperatures

The pre-fire period extends from Dec. 30, 2009 to Aug. 17, 2012. It was assumed that all salvage logging was completed within one year so the post-fire period during which salvage logging occurred, is defined as ending one year after the fire was fully contained, i.e. Aug. 31, 2013. Most of the trends are not visually striking, except at CC2 (Fig. 8), which seems to have reversed direction after the fire. For the full monitoring period, statistically significant increases were detected at CC and RC, while decreases were detected at BCT and DC, which are both above the fire zone, and NFB based on the adjusted Mann-Kendall trend test with Bonferonni critical $\alpha=0.0038$ (13 tests). Looking closer at these plots, we can see that the pre-fire data (Fig. 9) displays downward trends at almost every site. Seven of these trends are statistically significant ($p < 0.0038$). Most sites other than the spring in Canyon Creek (CCSP) were cooling during this period relative to that predicted from the model. The measurement instrument was changed from the Hanna meter to the pool thermometer in the pre-fire period, but that could account for no more than 1°C change, and the trends remain visible at nearly all the sites in the 10-month sub-period after the change in instrumentation.

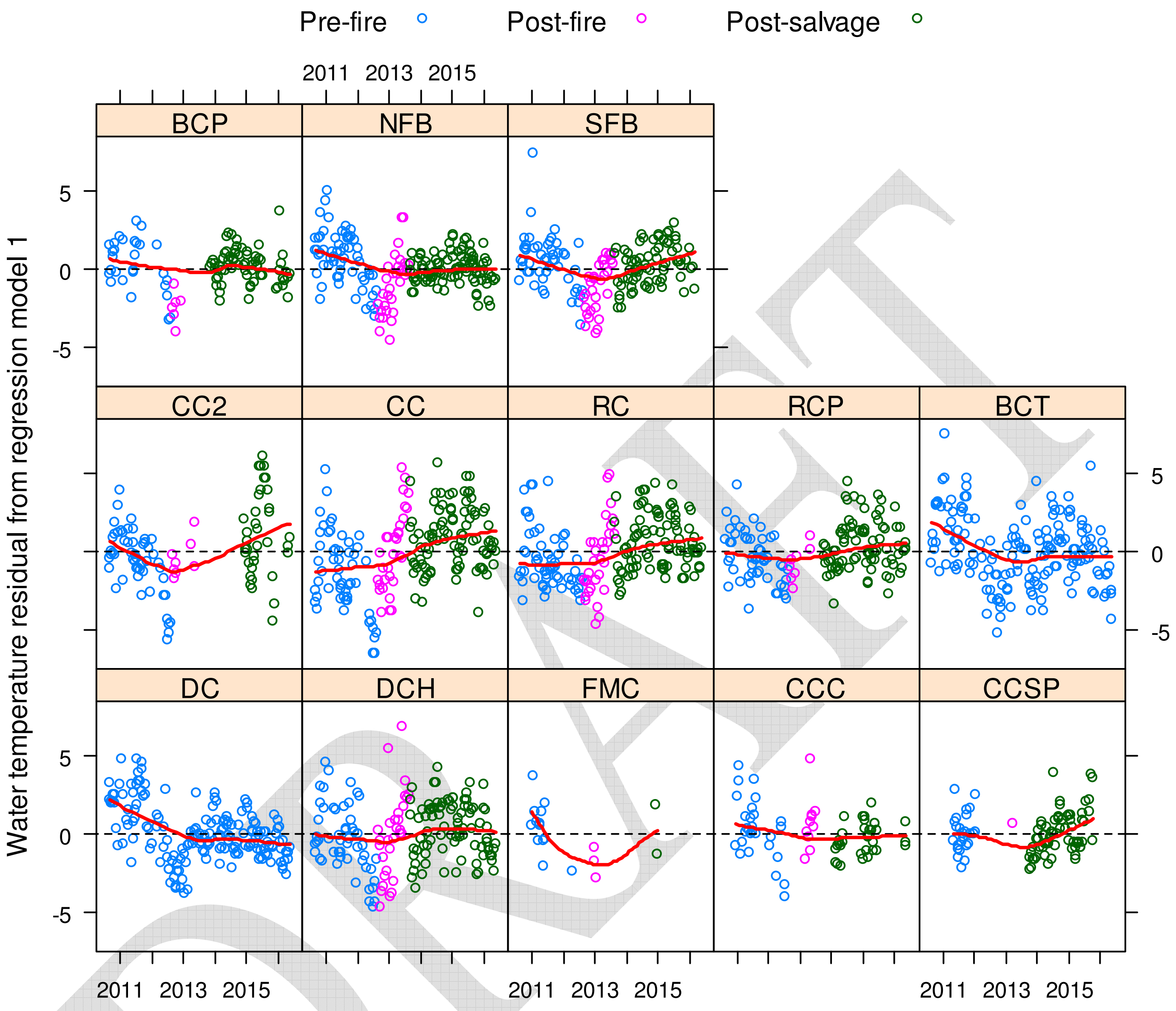

Figure 8. Trends in the residuals from model 1. The heavy red lines are loess smooths of the data (Cleveland and Devlin, 1988).

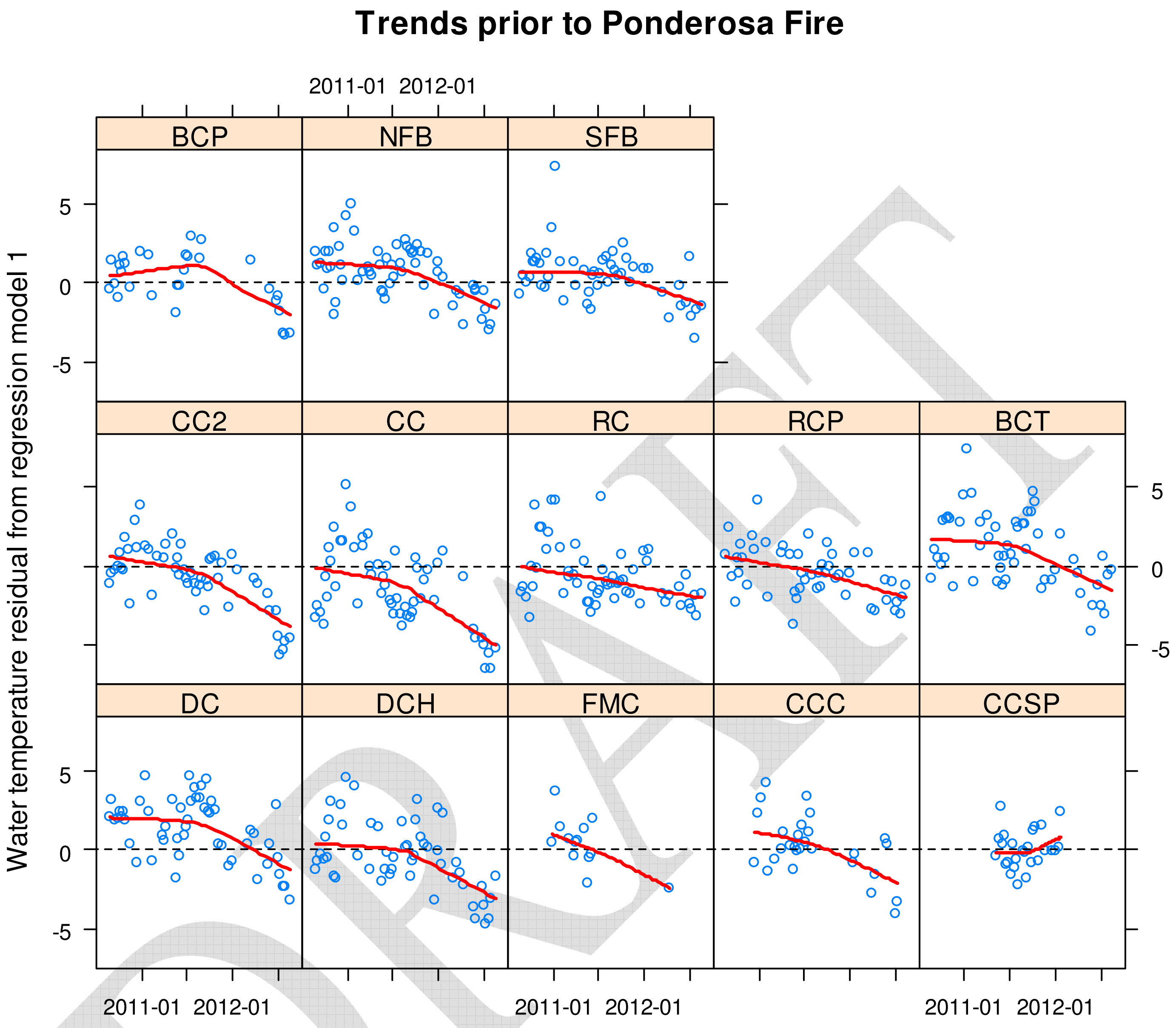

Figure 9. Trends in the residuals from model 1 prior to the Ponderosa Fire. The heavy red lines are loess smooths of the data (Cleveland and Devlin, 1988).

During the year after the fire, when salvage logging was conducted, all the sites with 10 or more measurements experienced a warming relative to predictions for model (1) based on air temperature and month (Fig. 10). It would be easy to attribute this warming to the salvage logging, except that unburned sites BCT and DC also experienced warming during this period. We can isolate the effect by comparing the changes at DC with those at DCH, which is 8 km downstream. The watershed between the two sites was almost entirely burned and salvage logged down to the stream. Linear trendlines were fitted to the DC and DCH scatterplots in Figure 10 and the difference in slopes was tested using a one-sided hypothesis by comparing the statistic $t = (b_1 + b_2)/(s_{b_1}^2 + s_{b_2}^2)^{0.5}$ to a Student's distribution with 54 degrees of freedom (the sum of those from the two regressions). The slopes differ significantly (p=0.0155), and over the 365-day post-fire period site DCH warmed an average of 1.8°C more than DC, based on the difference in regression slopes. The slopes of linear trendlines fitted to the 7 significant trends in Figure 10 are correlated (r=0.614) with the percentages of salvage logging that occurred during this period in each watershed (Fig. 11), however the association in this small sample is not statistically significant (p=0.11). Recall that because of diversions into SFB, its water temperature is heavily influenced by conditions in NFB. For Figure 11, it is assumed that 70% of the area within the fire perimeter in the South Fork was salvage logged. Unsalvaged areas can be seen in the South Fork on the 2014 Google Earth image but it is difficult to delineate them and it was not attempted.

After salvage logging was completed, departures from the model predictions do not show any significant trends (Fig. 12) with Bonferroni critical α=0.0042 (12 tests), except at DC and CCSP.

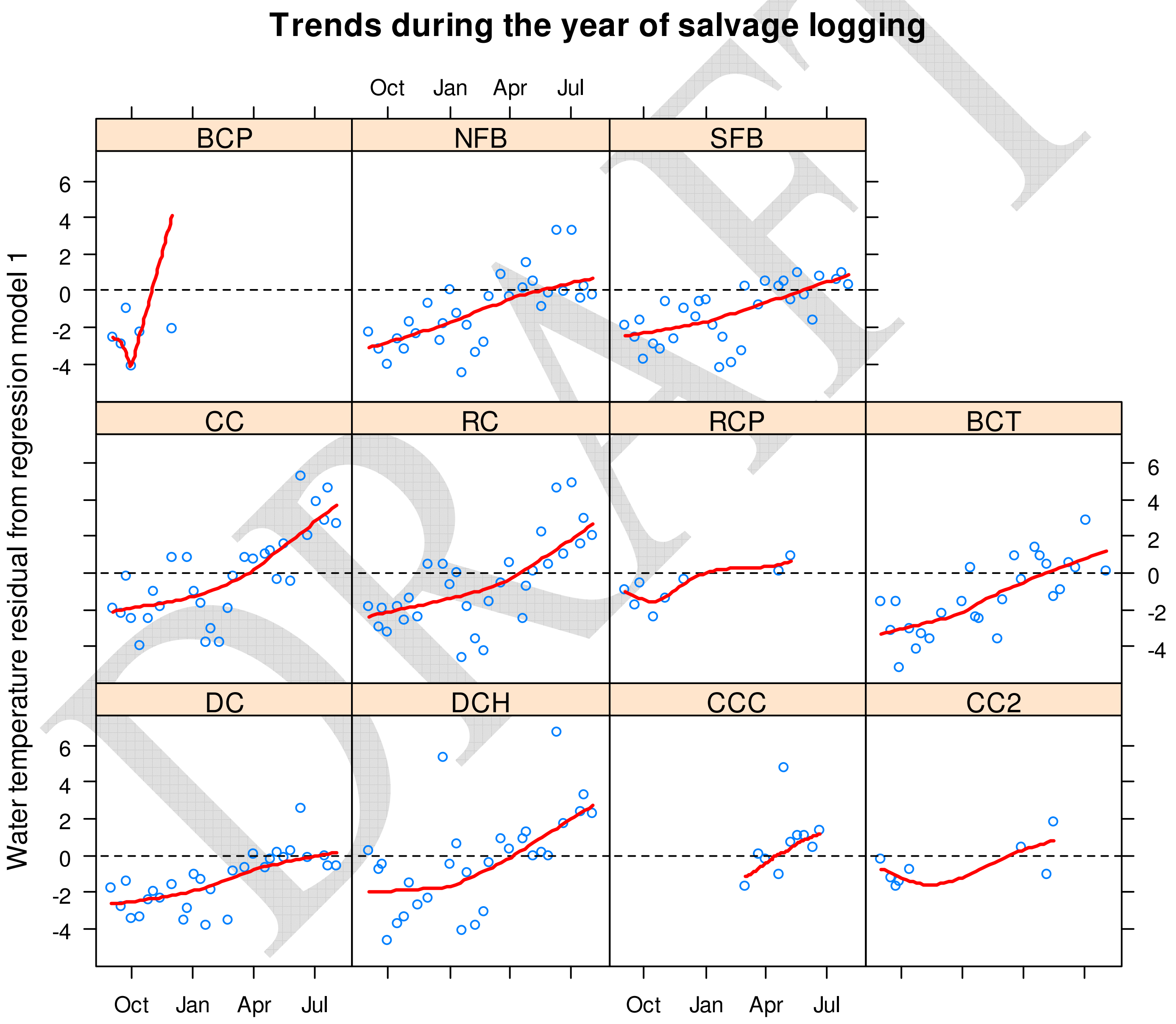

Figure 10. Trends in the residuals from model 1 during the year of salvage logging after the fire. The heavy red lines are loess smooths of the data (Cleveland and Devlin, 1988).

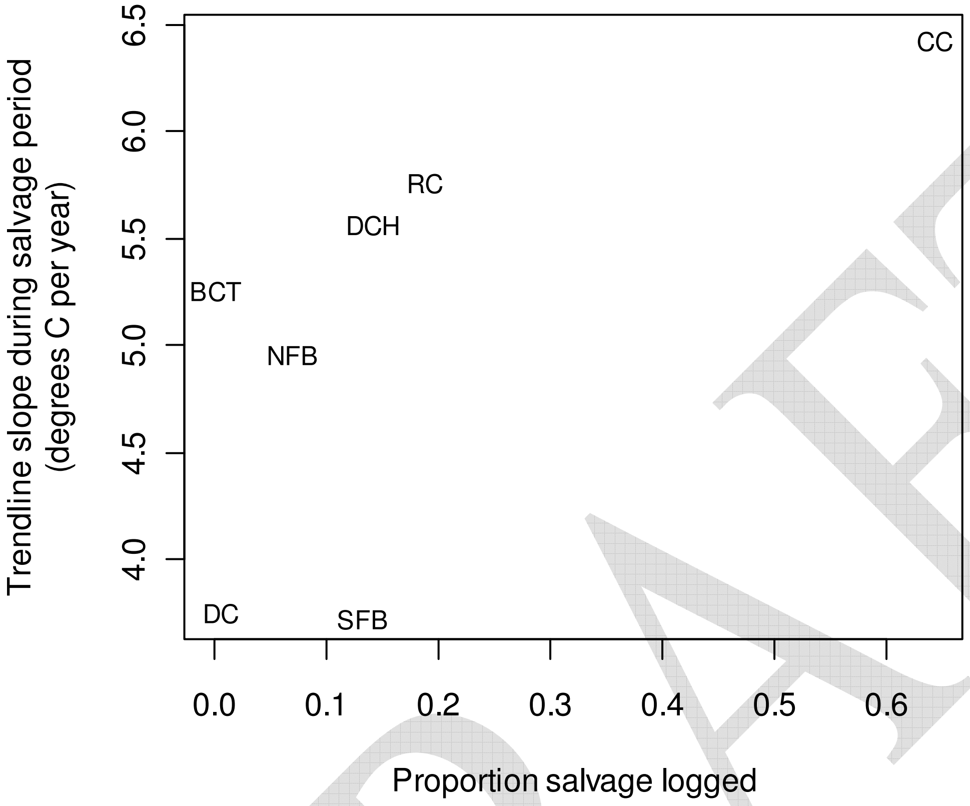

Figure 11. Slopes of trendlines fitted to Figure 10 scatterplots in relation to proportion of watershed salvage logged. Sites with non-significant trends are not included.

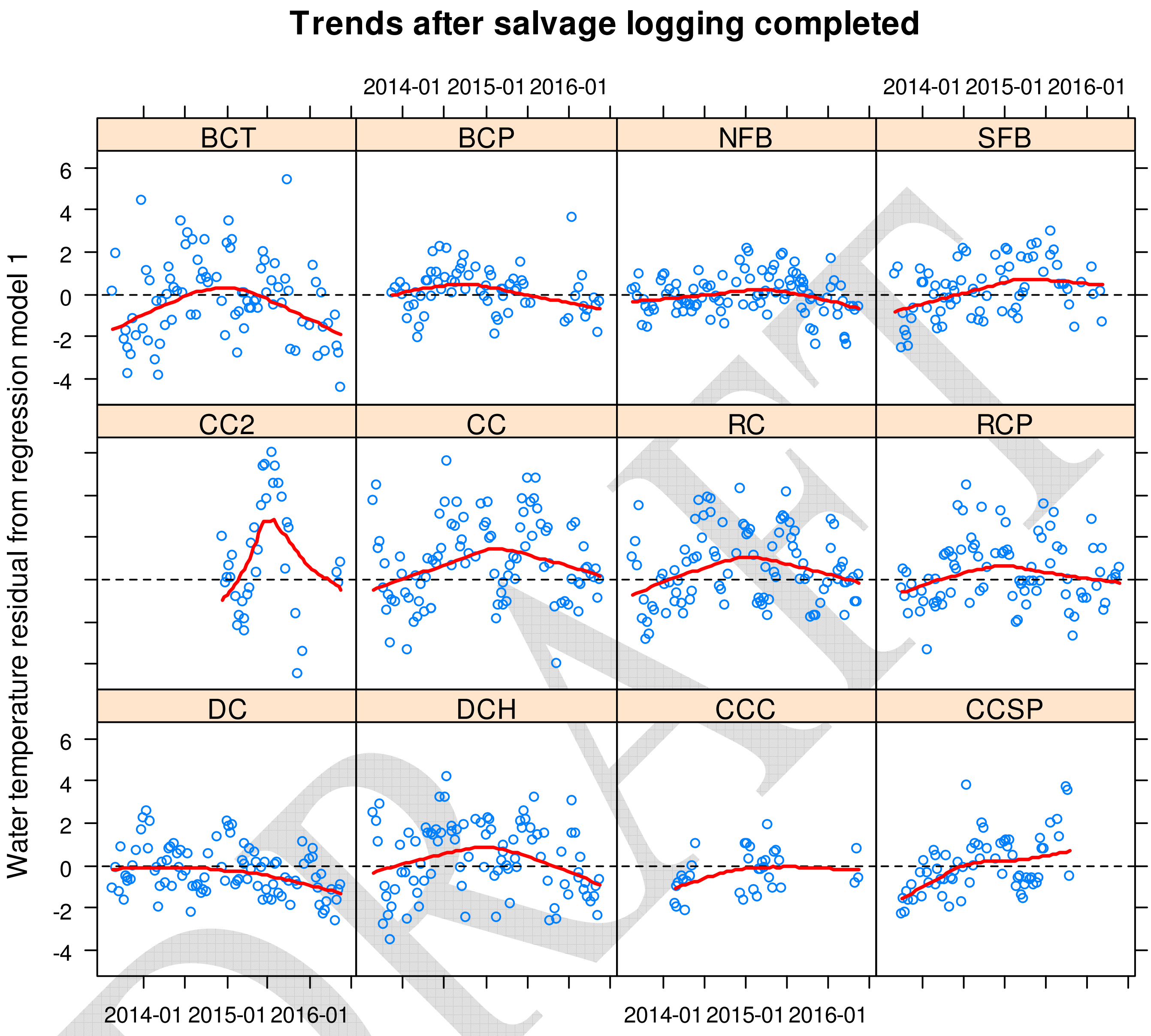

Figure 12. Trends in the residuals from model 1 after salvage logging was completed. The heavy red lines are loess smooths of the data (Cleveland and Devlin, 1988).

Summer temperatures

For salmonids, the most vulnerable months are during the summer when water temperatures are highest and can limit migration, holding, spawning, incubation, and emergence. Figure 13 shows the trends in residuals from model (1) during just the summer months, Jun 1 – Sep 30. The overall changes during the monitoring period are statistically significant ($\alpha=0.0042$) at CC, RC, RCP, DC, DCH, and CCSP. Some sites appear to have reversals in trend that cannot be detected by a test for monotonic trend. The first 4 post-fire residuals were measured on Sep 1, 16, 23, and 30 of 2012. At CC2 and CC, these 4 residuals (and 3 of 4 at DCH) are distinctly above the pre-fire cluster for that year but well below the 2013 values (2015 at CC2). These are interpreted as effects of the fire without salvage logging. The first post-fire residuals at other sites (RC, RCP, NFB, and SFB) unexpectedly do not show any increase from the pre-fire cluster for that year, but the residuals in 2013 are distinctly higher. The June-August 2013 points are shown as post-fire but, as we do not know the exact dates of the salvage logging, they may well have been measured after salvage logging was completed.

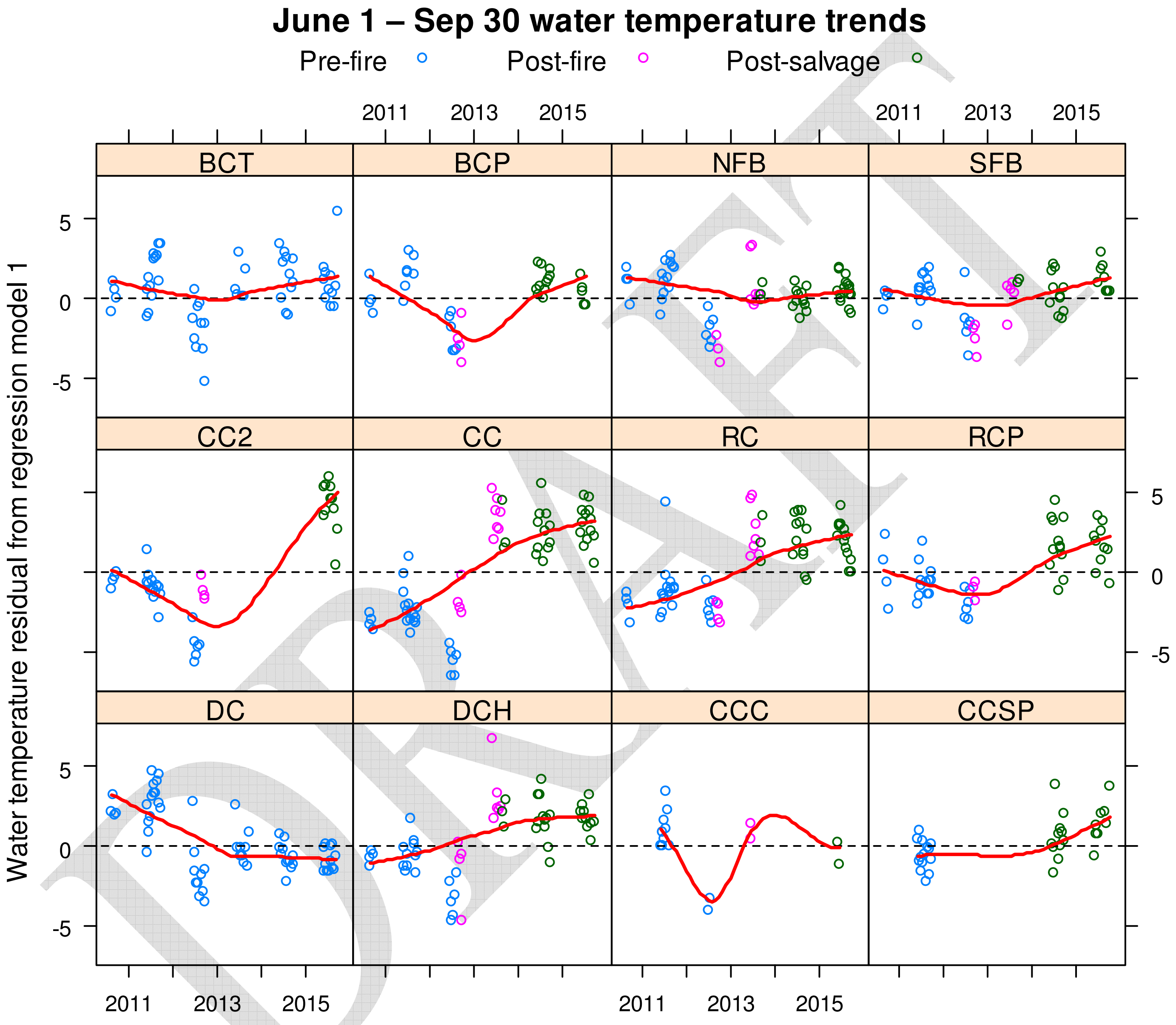

Figure 13. Trends in the residuals from model 1 during the summer season. The heavy red lines are loess smooths of the data (Cleveland and Devlin, 1988).

The changes in Canyon Creek are quite large. At CC from July-August to Septermber of 2012 the mean residual increased by 3.8°C and the increase widened to 8.8°C in summer of 2013. The analogous changes were 1.8°C and 6.0°C at DCH. At DC, upstream from DCH and unburned, the changes for these dates were only -1.2°C and 1.1°C. In watersheds other than CC, CC2, and DCH, there was no immediate water temperature effect from the fire, but a gradual increase was seen in residuals during the salvage logging period from the fall of 2012 through summer of 2013 (Fig. 10).

The increase in summer water temperature after the combination of wildfire and salvage logging was estimated from the 2012 and 2013 residuals in Figure 13 and is plotted against the proportion of watershed burned in Figure 14. The Pearson correlation coefficient (0.88) and Kendall's tau (0.60) are both significant (p=0.0003 and p=0.0099, respectively). Since even the unburned sites increased during this period, the values on the y-axis of Figure 14 cannot be attributed entirely to wildfire and salvage logging, but the slope of the relationship (4.0°C) is a rough estimate of the effect on a 100% burn. Of course, the spatial distribution of disturbance in relation to the stream channel is an important factor that has not yet been considered. We can estimate the amount attributable to wildfire and salvage logging in particular cases by comparing changes in upstream-downstream pairs. The mean change was 4.6°C more at DCH than at DC. The mean change was 0.7°C more at BCP than at BCT but there is a cold-water spring shortly upstream from BCP, which explains the very muted affect at BCP relative to BCT.

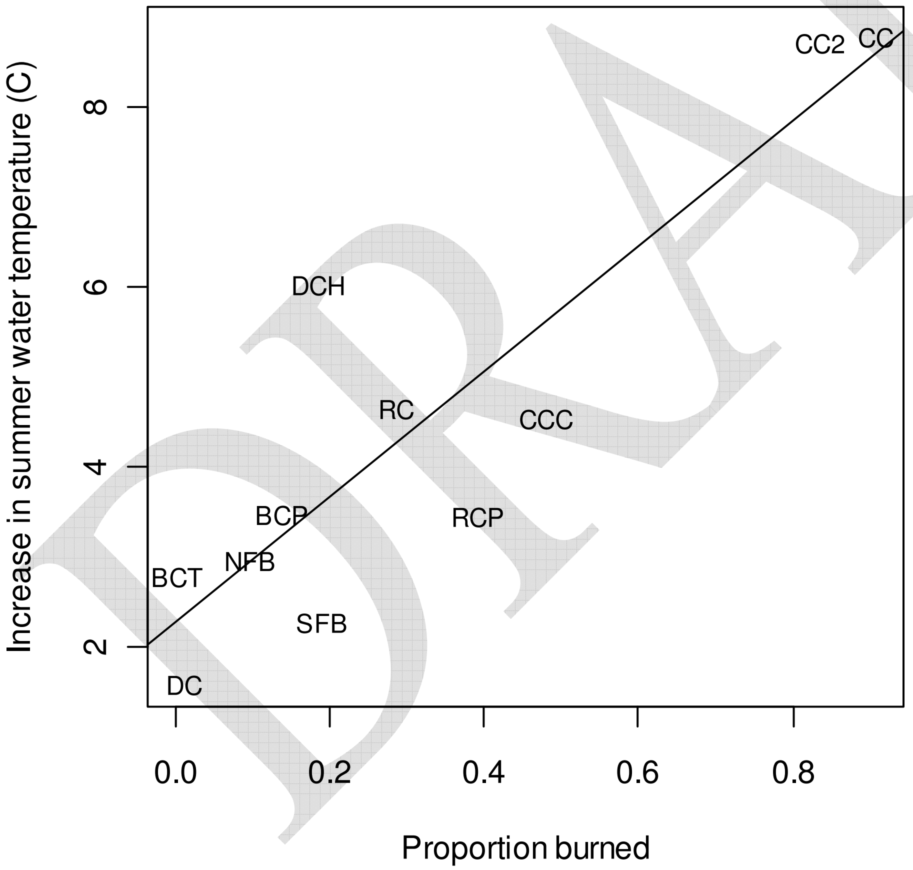

Figure 14. Increase in summer water temperatures plotted against proportion of watershed burned. Increases are estimated from pre-fire residuals in 2012 and post-fire and post-salvage residuals in 2013.

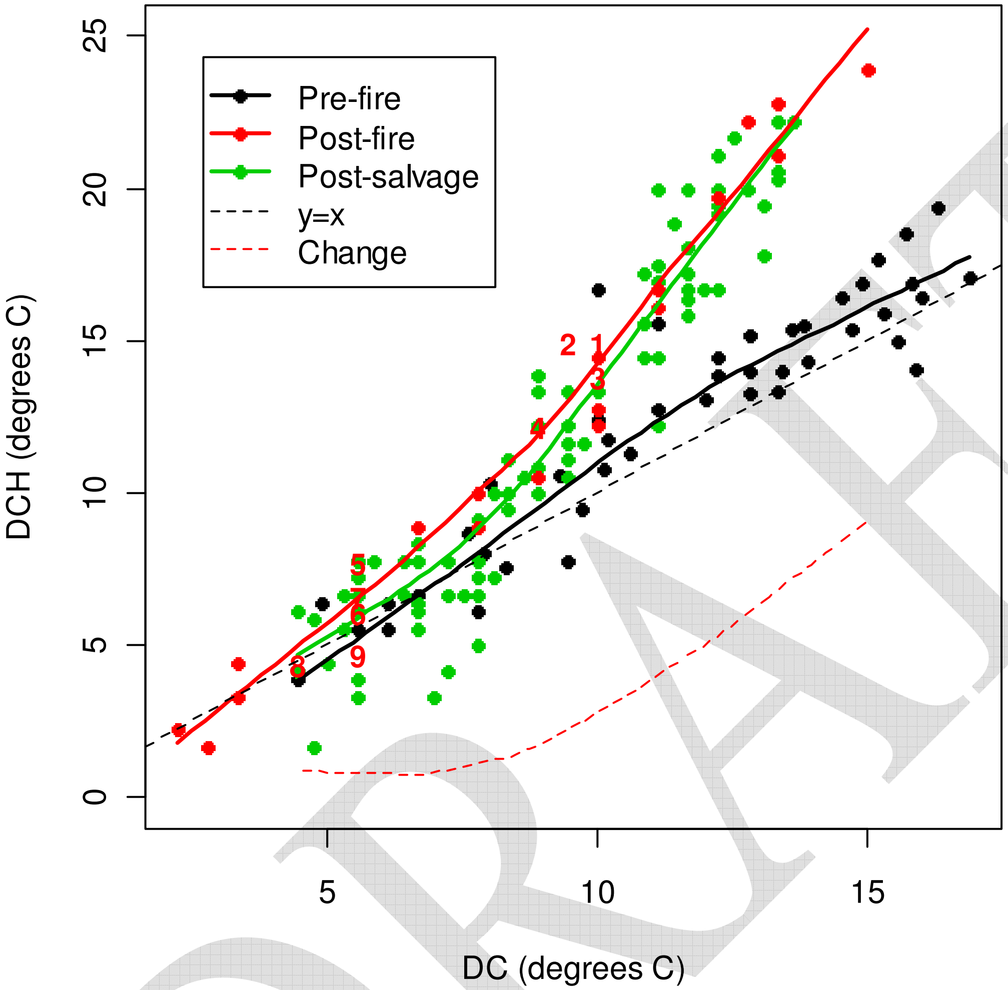

Figure 15. Relationships between temperatures measured at DCH and DC on the same day. The dashed red line is the difference between loess fits to the pre-fire data and the combined post-fire and post-salvage data. The first 9 post-fire points, measured between Sep 1 and Nov 30, are plotted as sequence numbers in red.

Digger Creek upstream-downstream analysis

The relationships between water temperatures at stations DC and DCH in Digger Creek are indistinguishable before and after the Ponderosa Fire (Fig. 15) for temperatures below about 7.5°C at station DC, but at warmer temperatures above 10°C at DC, the separation is dramatic. Loess curves were fitted to the data from each of the three monitoring periods. There is no clear division between data collected during the post-fire and post-salvage periods. Measurements collected in the first 3 months after the fire are not systematically lower or higher than later measurements. The mean temperature at DCH for any given temperature at DC was within 1 or 2 degrees of the temperature at DC during the pre-fire period. A loess curve was also fitted to the combined post-fire and post-salvage data (not shown in Fig. 15). The difference between the combined post-fire curve and the pre-fire curve is shown as the dashed red line in Figure 15. After the fire, temperatures at DCH averaged less than 1°C higher than DC when DC was below 7.5°C but differences increased rapidly to 9°C when the temperature at DC was 15°C.

Maximum daily water temperatures

I estimated hourly summer water temperatures, applying the *composite* method of Aulenbach and Hooper (2006) with the regression expression (1). The composite method was applied separately with different regression coefficients before and after the Ponderosa fire. After accounting for day number, coefficients for mean daily discharge were not significant so those terms were dropped from the regression equations. Daily maximum hourly temperatures are displayed by year for upstream-downstream sequences in Digger, Canyon, Rock and Bailey Creeks (Figs 16-19), and for the North and South Forks of Battle Creek (Figs. 20 and 21).

At Digger Creek, maximum summer water temperatures at DCH tracked those upstream at DC fairly closely in 2010 and 2011 (Fig. 16). Starting late in June 2012, after portions of the watershed between the two stations had been clearcut, the DCH maxima started to rise while those at DC continued to decline. The clearcuts (about 75 ha) did not extend to Digger Creek but did include some surface water in smaller tributaries. DCH was affected heavily by the fire in late August but no salvage logging occurred until after September. Salvage logging removed a great number of burned trees from the riparian zone and, from June to early September of 2013, maximum water temperatures in DCH were 8-10°C higher than in DC, exceeding 20°C on most days. The 2013 temperature pattern persisted in the summers of 2014 and 2015.

In Canyon Creek, no harvesting occurred during the monitoring period until after the Ponderosa fire. Maximum summer water temperatures at the upper site, CCC, were about 1 degree lower in 2010 than those in CC2 and CC (Fig. 17). In 2011 temperatures were quite similar at all 3 sites, averaging about 15°C. In 2012, about 48% of CCC was lightly burned and 22% was subsequently salvage logged. Disturbance was much greater downstream at CC2, where 84% was burned and 59% was salvage logged. Further downstream at CCC, 91% was burned and 64% salvage logged. Maximum summer temperatures at CCC in the fall of 2012 did not increase in response to the fire, while those at CC2 and CC jumped by about 5°C. In 2013, 2014, and 2015, maxima in both CC2 and CC exceeded those upstream in CCC by 6-10°C. Maxima in CC in 2013 and 2014 were about 1°C greater than in CC2. Post-fire maxima at CC2 and CC were typically in the 20-25°C range, and exceeded 25°C 4-9 days per year at CC.

In Rock Creek, no harvesting occurred during the monitoring period until after the Ponderosa fire. Maximum summer water temperatures were very similar at the RC and RCP sites in 2010 and 2011, typically in the 15-20°C range (Fig. 19). In late August of 2012, about 29% of RC and 39% of RCP burned in the Ponderosa Fire but in September there was no obvious change in maximum temperatures; both sites experienced maxima similar to those in 2010 and 2011. By 2013, 19% of RC and 27% of RCP had been salvage logged and summer maxima were distinctly higher, particularly at RC in June and July. In 2014 and 2015, RC and RCP responded similarly, with maxima typically in the 20-26°C range until early September.

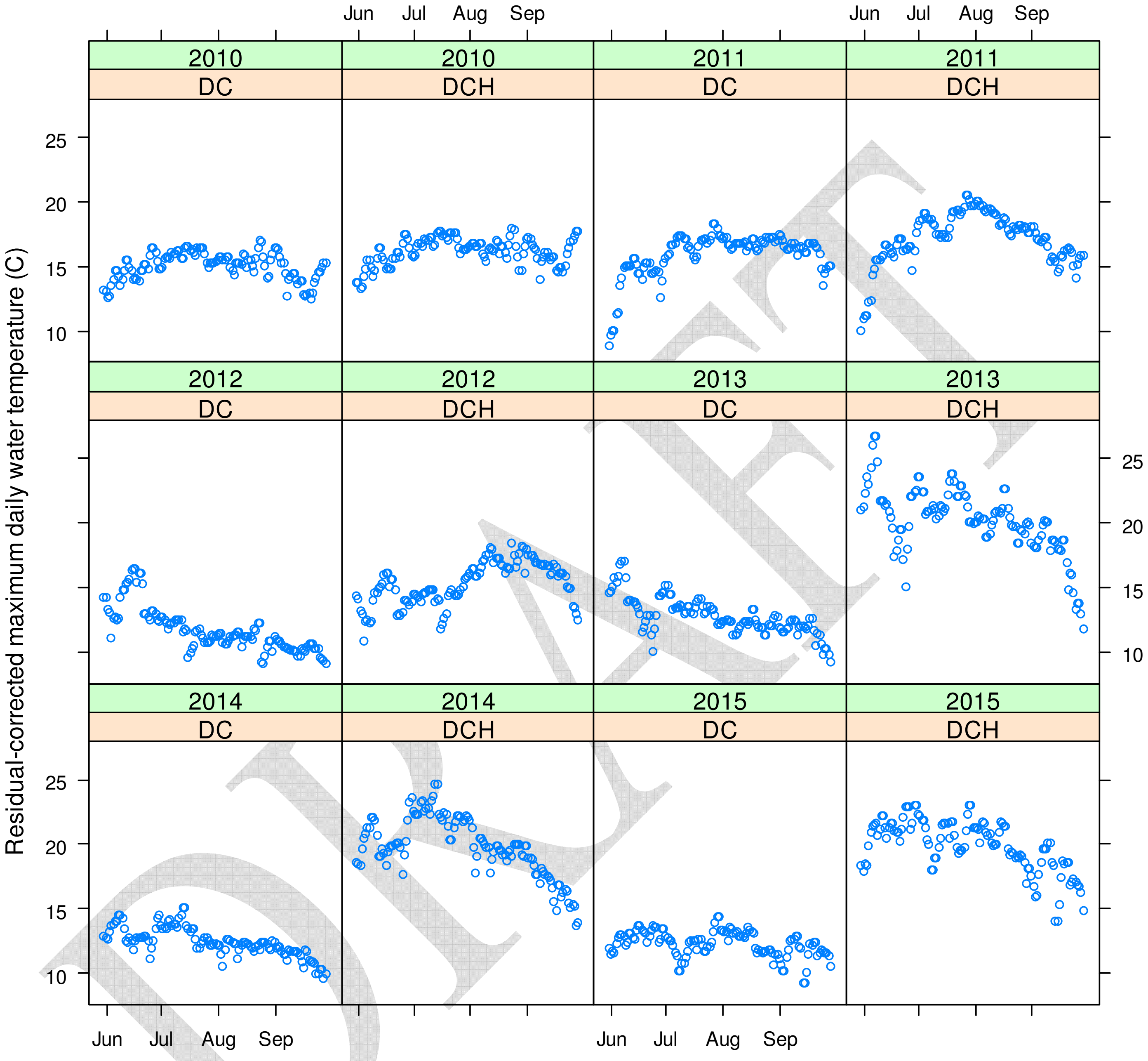

Figure 16. Estimated maximum daily water temperatures at Digger Creek stations DC and DCH.

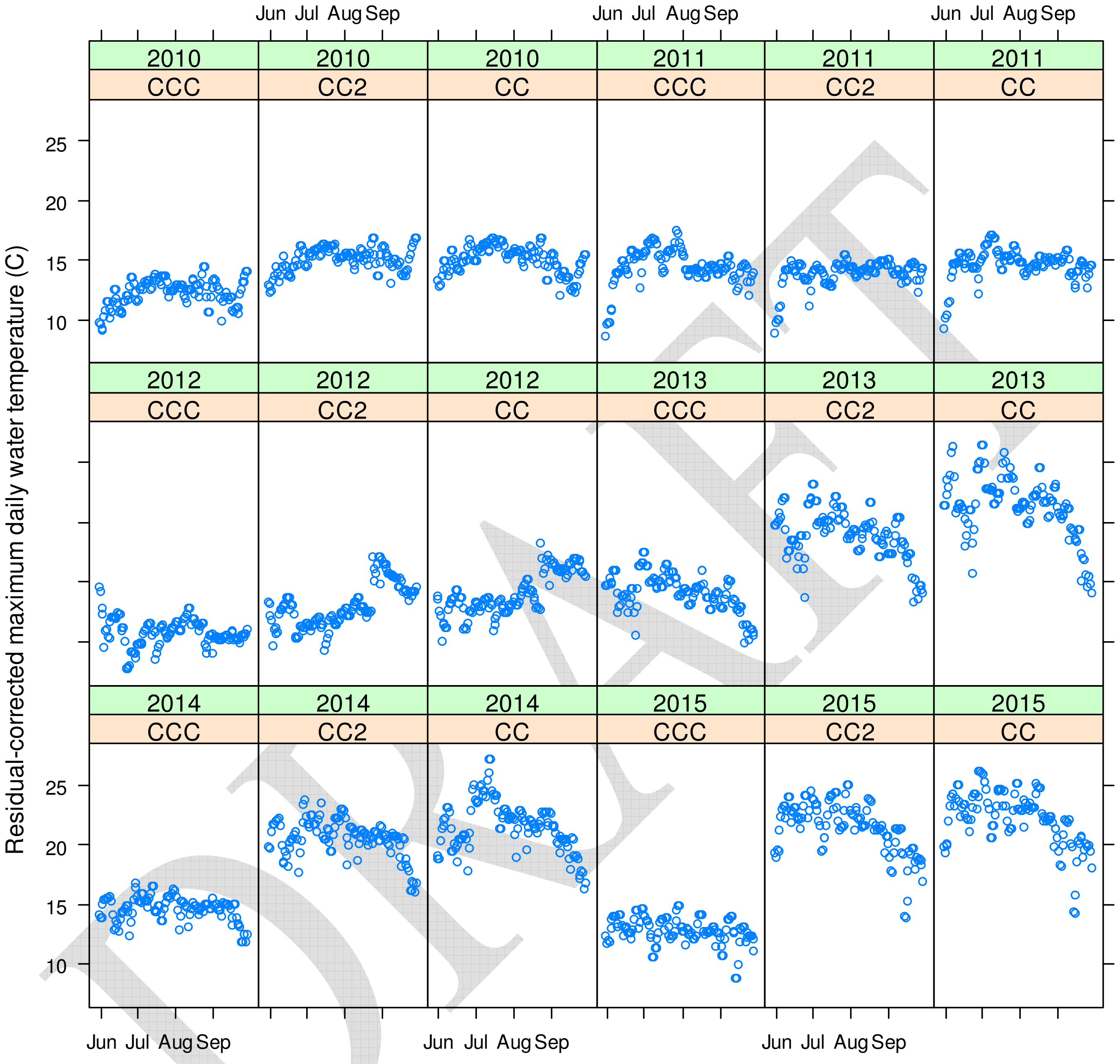

Figure 17. Estimated maximum daily water temperatures at Canyon Creek stations CCC, CC2, and CC.

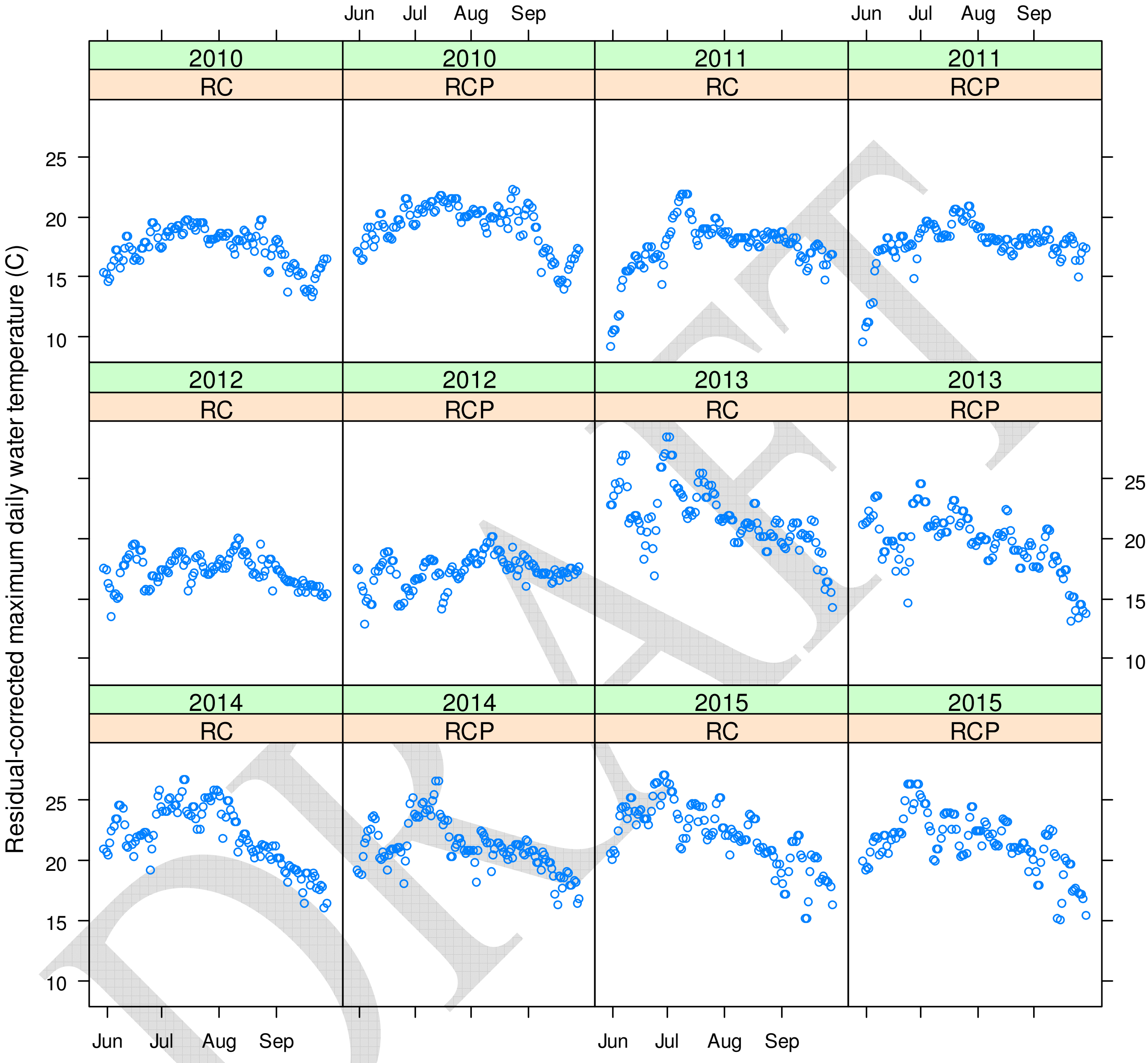

Figure 18. Estimated maximum daily water temperatures at Rock Creek stations RC and RCP.

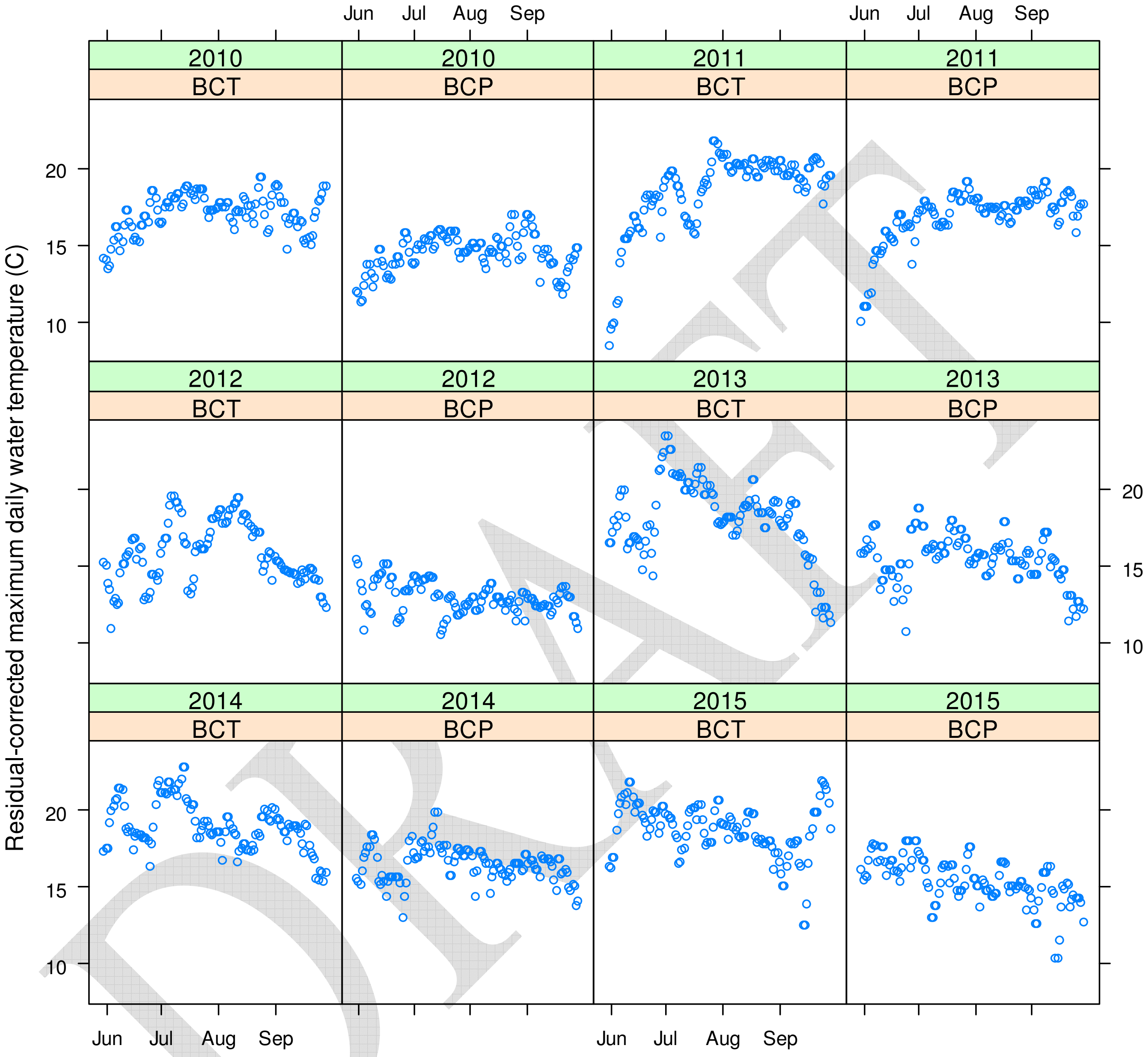

Figure 19. Estimated maximum daily water temperatures at Bailey Creek stations BCT and BCP.

In Bailey Creek, about 1.3% of BCT and 0.8% of BCP was harvested early in the summer of 2010. Due partly to the influence of a cold water spring entering the creek just above the lower site (BCP), maximum summer water temperatures at BCT exceeded those at BCP by 2-3°C in 2010 and 2011 (Fig. 19). Temperatures at both sites were warmer in 2011 than 2010, with many maxima exceeding 20°C at BCT. About 14% of BCP burned in the Ponderosa fire, and about 11% was subsequently salvage logged, while BCT was upstream and unaffected. Maxima at BCP were generally below 15°C in 2012, and in September there was no apparent response to the fire. Maxima upstream at BCT exceeded those of BCP by 5°C in July and August. In 2013 maxima were greater at both BCT and BCP but maxima at BCP did not rise more than those at BCT. About 1.6% of BCT and 4.2% of BCP was harvested in the summer of 2014. Maxima remained elevated at both stations in 2014 and 2015, with maxima at BCP continuing to average 2.5-3°C below those at BCT.

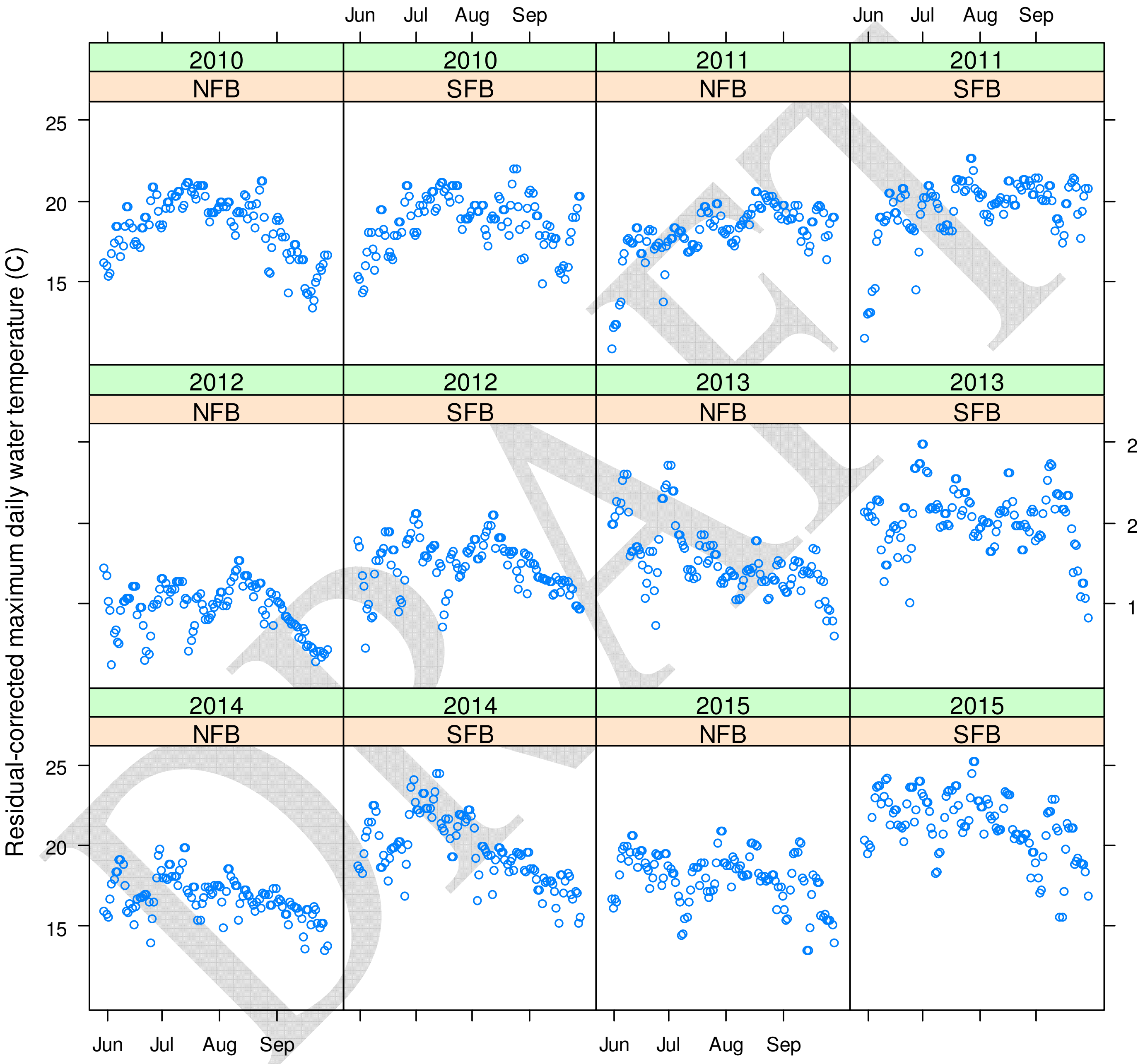

Figure 20. Estimated maximum daily water temperatures at Battle Creek stations NFB and SFB.

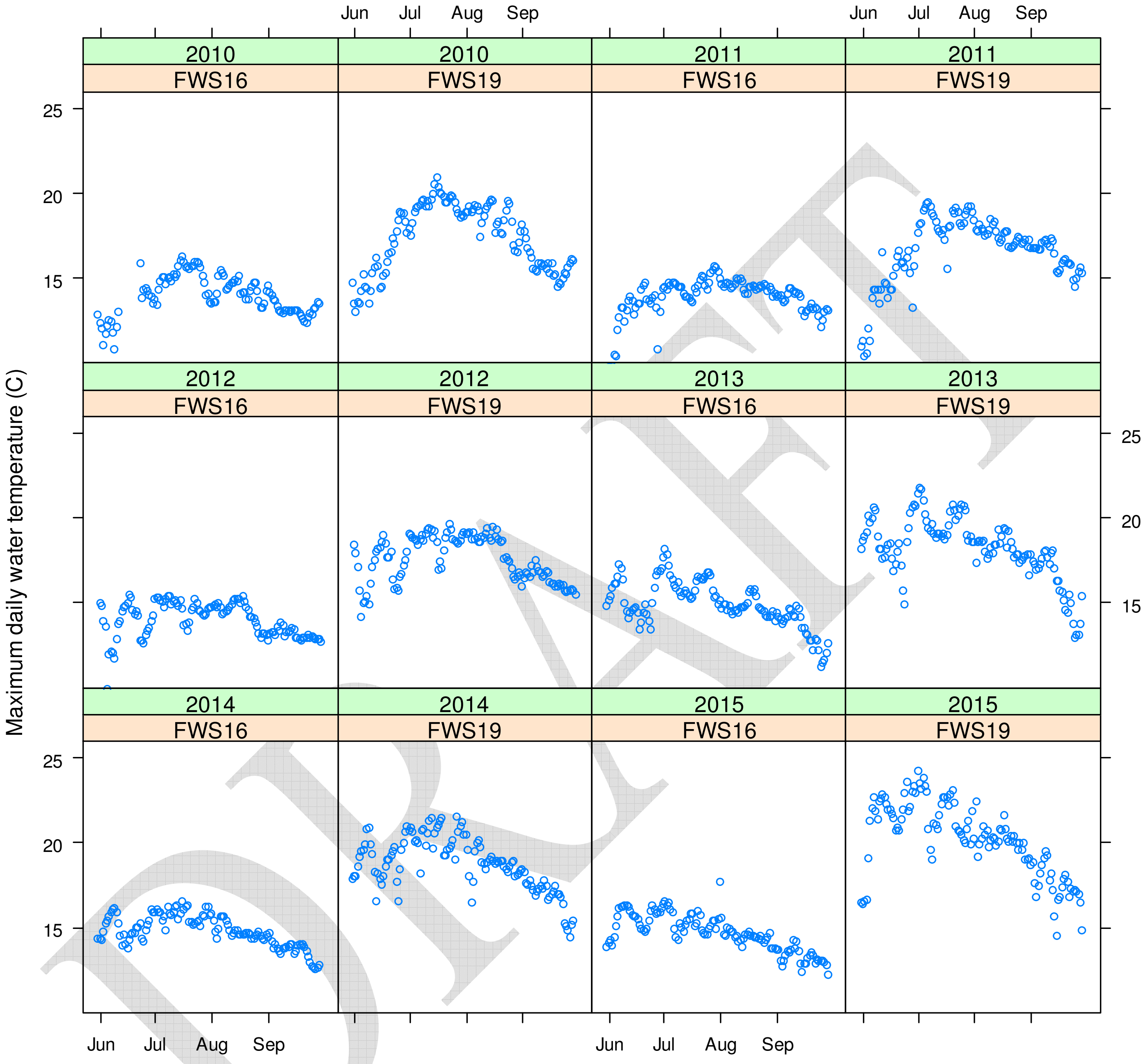

Figure 21. Maximum daily water temperatures measured by Hobo loggers at FWS sites 16 (near NFB) and 19 (near SFB) on the North and South Forks of Battle Creek.

Maximum summer water temperatures in 2010 were quite similar at NFB and SFB, generally in the 15-22°C range, but in subsequent years SFB grew progressively warmer than NFB. Maxima at NFB were cooler in 2012, and neither site showed a response to the fire in September of 2012. Stream temperatures were warmer at SFB in 2013 and remained elevated (mostly above 20°C) in 2014 and 2015. At NFB, summer maxima were much higher in early summer following the fire, but then dropped back to the 15-20°C range and have stayed in that range. Maxima at SFB have increased relative to those at NFB, growing from an average of 0.3°C in 2010 to 3.4°C in 2015. The growing differences between SFB and NFB may be influenced by the varying water transfers between the watersheds. Conveyances from the North Fork to the South Fork have declined since 2012, while exports from the South Fork have increased (Fig. 5). Another factor that could be influencing the higher temperatures in the South Fork is a recent large influx of sediment and filling of pools and runs that has been reported by FWS (Brown, 2015).

Water temperatures are measured using Hobo data loggers by FWS near NFB at their site 16 (near Volta Powerhouse and about 0.7 km upstream from NFB) and at site 19 (Manton bridge, same location as SFB). Summer daily maxima are shown in Figure 21 for comparison to Figure 20. The FWS values at site 16 average 2.8°C lower than at NFB, while the values at site 19 average 1.3°C lower than at SFB. FWS values also display less scatter. Although the FWS data indicate that the North Fork started cooler than the South Fork (in 2010), the overall trends are similar to those in Figure 20, with the South Fork warming more than the North Fork after the fire. The North Fork (site 16) stayed in a fairly confined range below 16°C prior to the fire with maxima briefly reaching 18°C in 2013 and 17°C in 2014 and 2015. Maxima in the South Fork (site 19) peaked near 20°C in the pre-fire years, but increased subsequently to 22°C in 2013 and 2014 and 24°C in 2015. Temperatures at site 19 exceeded 22°C on 28 days in 2015. The median difference between June-September temperatures at sites 16 and 19 grew from 2.9°C in 2011 to 5.8°C in 2015. The percentage of the SFB watershed that burned was approximately double that of SFB (19.0% versus 9.6%).

The maximum daily temperatures may be summarized in various ways for considering the effects on salmonids. Annual MWMT are shown in Figure 22. Because measurements were spaced approximately 2 weeks apart in summer, the residuals have a persistent influence on residuals-corrected MWMT and if temperature conditions are ephemeral this could introduce errors. Therefore, both the uncorrected and corrected versions are shown in Figure 22. The MWMT estimated from BCA measurements is plotted along with that determined from FWS Hobo loggers at sites 16 and 19 in Figure 23. BCA values for NFB average 3.1°C higher. BCA values of MWMT for SFB average 1.5°C higher than FWS values in 2010-2014, but in 2015 the FWS value exceeds that estimated from BCA data by 0.6°C.

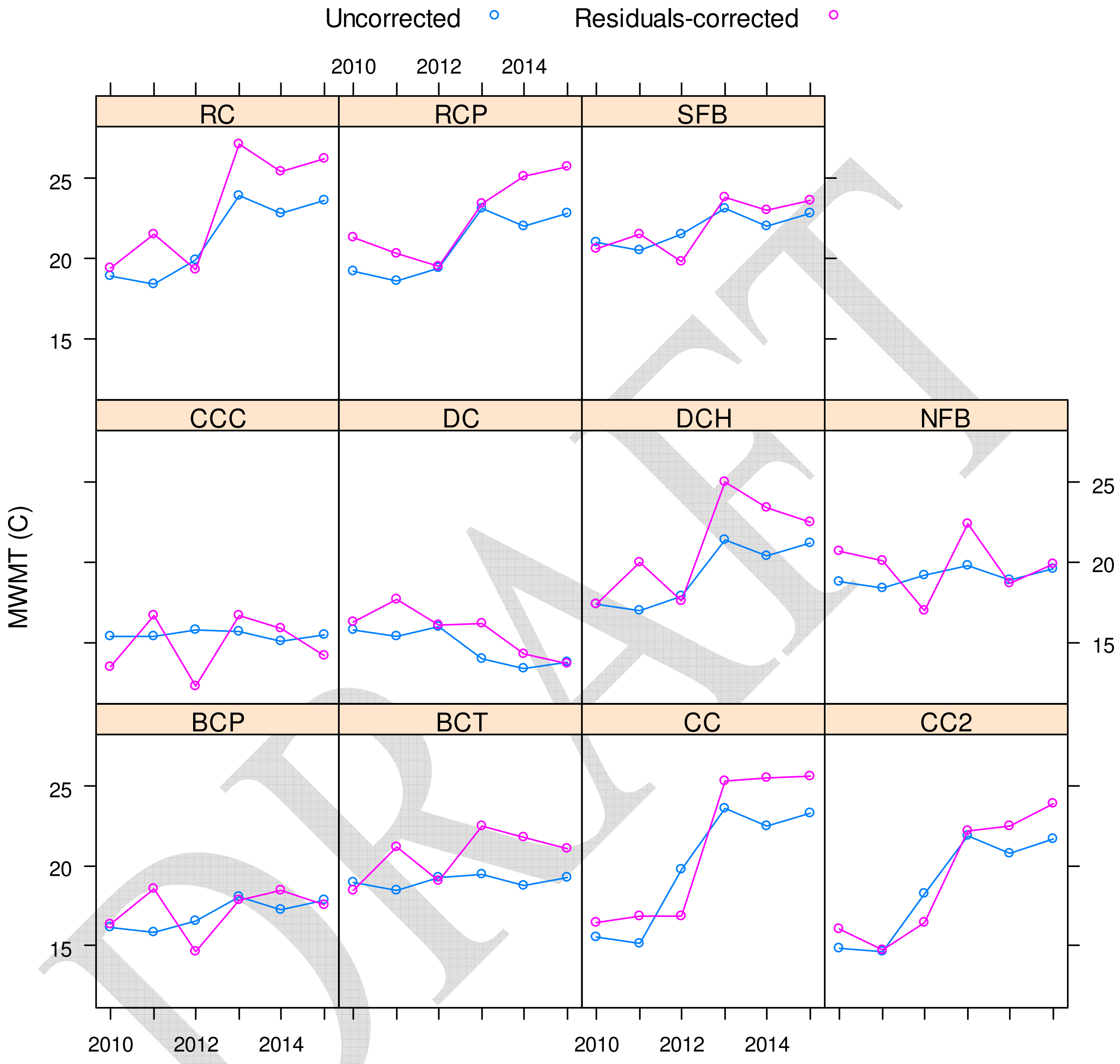

Figure 22. Annual MWMT, estimated from pre-fire and post-fire regression models, with and without composite method residual corrections.

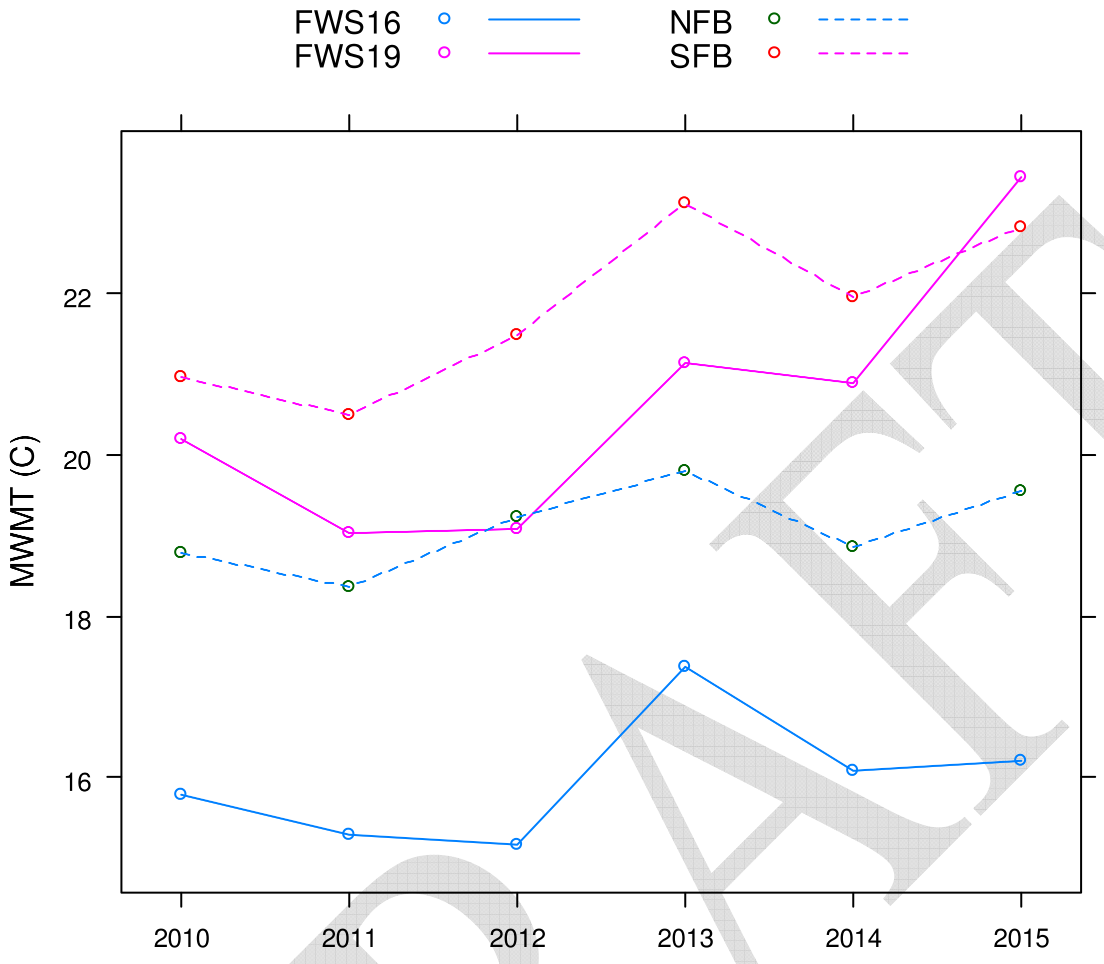

Figure 23. Annual MWMT at BCA sites, estimated from pre-fire and post-fire regression models, and at FWS sites, measured using Onset Hobo data loggers. FWS16 is near NFB and FWS19 at SFB.

To place the temperatures shown in Figures 22-23 in context, the following MWMT thresholds were obtained from Carter (2005). USEPA (2003) concluded that MWMT < 20°C would permit migration of juveniles and adults, and that temperatures > 22-24°C eliminate salmonids from a location. WDOE (2002) advises that the MWMT should not exceed 17-18℃ to be fully protective of adult steelhead migration. USEPA (2003) concluded that MWMT should not exceed 13°C to be protective of spawning, egg incubation, and fry emergence. To avoid serious rates of infection and mortality the MWMT should not exceed 17.4°C, and severe infections and catastrophic outbreaks become a serious concern when the MWMTs exceed 20.9°C (WDOE, 2002).

Stations affected severely by the fire (CC, CC2, RC, RCP, SFB, DCH are clearly inhospitable (MWMT>20°C) for steelhead and chinook migration or holding during the summer months, whereas prior to the fire, the MWMT for all 3 sites on Canyon Creek was safe (MWMT ≈ 15°C) for migration and holding. The Rock Creek stations (RC and RCP), lower Digger (DCH), and SFB were borderline for migration (MWMT ≈ 20°C) prior to the fire. Temperatures in the lightly burned CCC and unburned DC remain in a protective range (MWMT < 17-18°C) for adult steelhead and chinook migration, while spring-fed BCP is borderline. NFB in 2015 is in a better condition (MWMT < 20°C) than SFB (especially based on FWS data), perhaps because less than 10% of its watershed burned and it may have cold-water influxes below the burn zone such as that enjoyed by BCP. Upper Bailey Creek (BCT) is warmer than upper Digger (DC), although the harvest and fire history and size are similar. The difference may be related to water withdrawals from Bailey Creek near the settlement of Viola.

Figures 24 shows monthly means (June – Sep) of maximum daily water temperature. The absolute values are smaller than the annual MWMT in Figure 22 but they tell a similar story. One sees that the post-fire maxima above 20°C are not high outliers but are typical. Some patterns related to treatment are revealed in the monthly values. Maximum temperatures in most years are in July. Notable exceptions occurred after the fire at stations CC, CC2, and DCH, when August and September MWMT exceeded July values. June and July were much higher in the years after the fire at sites CC, CC2, DCH, and RC, whose watersheds were all heavily burned. August and September MWMT were greater in 2013 (after salvage logging) than in 2012 (after the fire but before salvage logging), especially at sites affected by the fire, and most markedly in Canyon Creek.

The monthly values in Figure 24 are useful for comparison to salmonid thermal tolerances and critical periods that were identified in the Draft EIS (USBR AND SWRCB, 2005) for the BCRP (Table 3).

Table 3. Critical periods and thermal tolerances for priority species in Battle Creek, from Draft EIS (USBR AND SWRCB, 2005, citing Jones and Stokes, 2004).

Species and Life Stage	Critical period	Thresholds (°C)
Winter-Run Chinook Salmon Embryos	July	>16.7 (0% survival), 15.6-16.7 (50%), 14.2-15.6 (75-85%)
Winter-Run Chinook Salmon Juveniles	Sep	>24.7 (lethal), 13.6-24.7 (variable), 10-13.6 (preferred)
Spring-Run Chinook Salmon Smolts	Jun	>20 (unsuitable), 17-20 (marginal), 10-17 (optimum)
Spring-Run Chinook Salmon Adults	Jul, Aug	>18.9 (unsuitable), 15.6-18.9 (stressed), 10-15.6 (preferred)
Steelhead Smolts	Jun	>15 (unsuitable), 13-15 (marginal), 6-13 (optimal)

In the past 3 years winter-run Chinook salmon embryos would have not been able to survive in July at any of the monitored sites except CCC (survival about 50%) and DC (survival better than 75%). Survival of juveniles in September would have been "variable", except at DC where temperatures were "preferred". Spring-run chinook smolts in June would have encountered "unsuitable" temperatures everywhere except BCT and NFB (where conditions were "marginal") and CCC, DC, and BCP (where conditions were "optimal"). Temperatures for spring-run adults in July and August have been "unsuitable" everywhere except CCC and DC (where conditions were "preferred") and BCP and NFB (where adults would have been "stressed"). Conditions for steelhead smolts in June have been "unsuitable" everywhere except CCC and DC (where they were "marginal").

Based on the FWS Hobo data (Figure 25), recent conditions at site 16 in the North Fork (but not the South Fork) are better than that described in the previous paragraph. Winter-run Chinook embryo survival is expected to be about 50% in the North Fork, while juveniles would be at the upper boundary of their "preferred" range. Spring-run chinook smolts and adults have optimum or near-optimum temperatures. However, temperatures measured at site 16 are still too warm for steelhead smolts. In the South Fork at site 19, June and August mean daily maxima have exceeded 18°C for the past 3 years and July mean daily maxima have exceeded 20°C. Thus it is clear that temperatures in the past 3 summers have been unsuitable in the South Fork for 3 of the life stages in Table 3 and variable or marginal for the others.

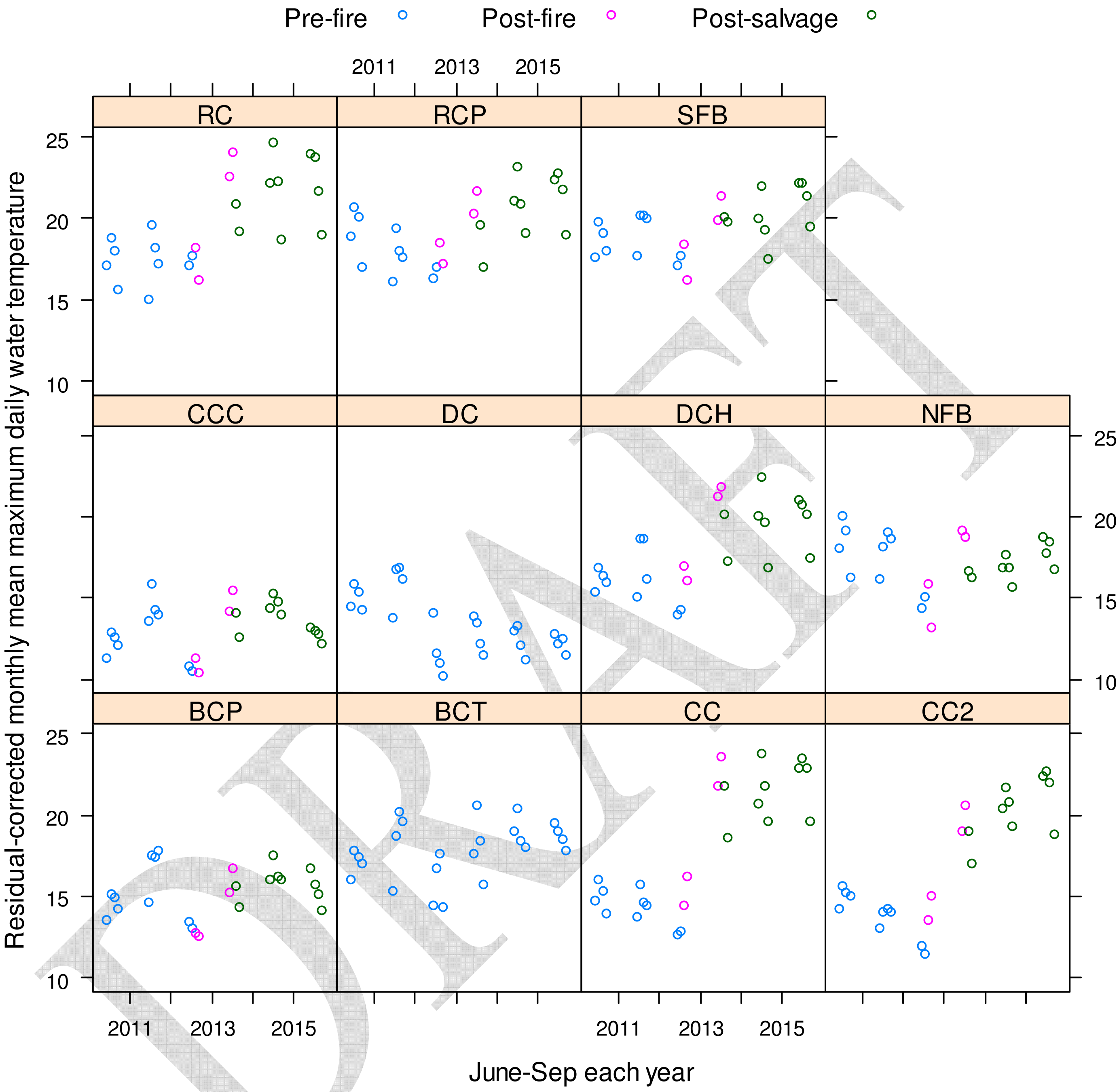

Figure 24. Monthly means of maximum daily water temperature, estimated from pre-fire and post-fire regression models with composite method residual corrections.

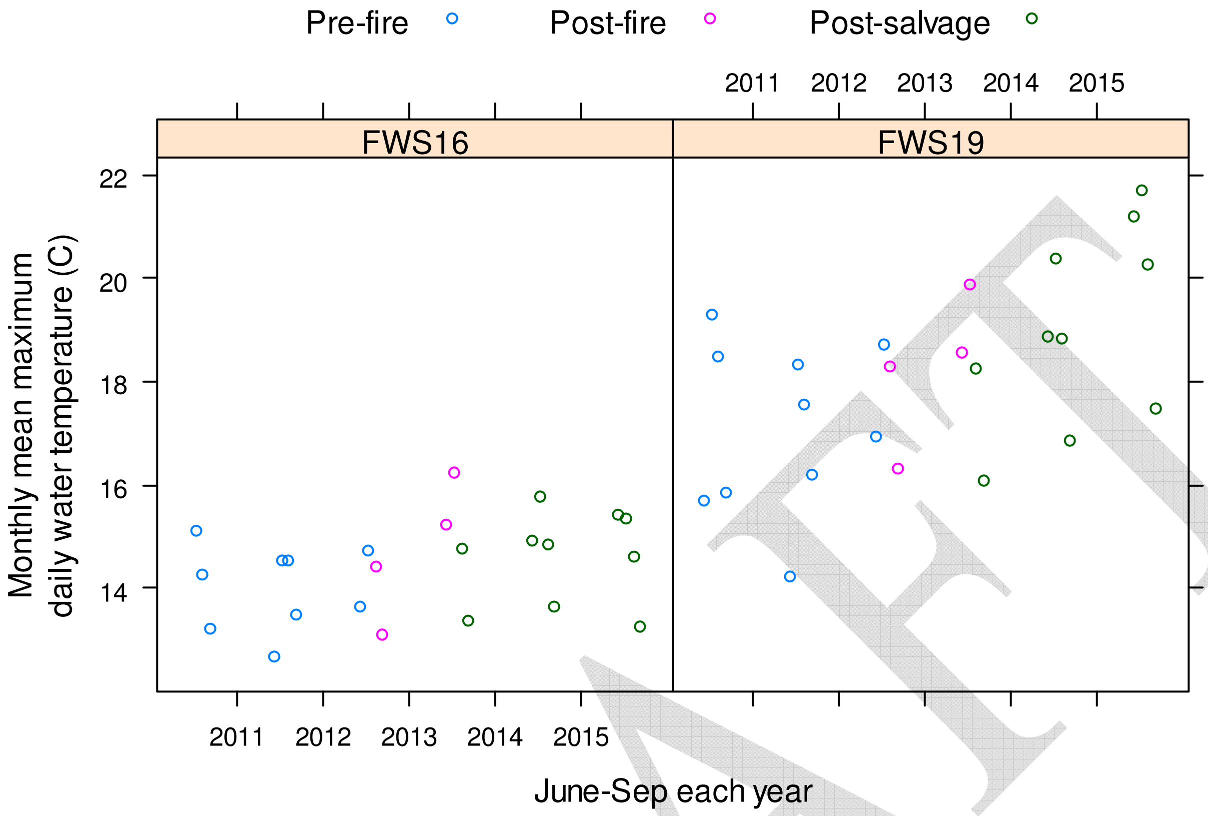

Figure 25. Monthly means of maximum daily water temperature, measured with Hobo loggers at USFWS sites 16 (near NFB) and 19 (same location as SFB).

SUMMARY AND DISCUSSION

For the full monitoring period, statistically significant increases were detected at CC and RC, while decreases were detected at BCT, DC, and NFB. These were not continuous trends that persisted through the monitoring period—they reflect changes that occurred within shorter time windows. All stream monitoring sites experienced a cooling trend (after accounting for air temperature trends) prior to the Ponderosa Fire. A reasonable guess as to the cause of the cooling is vegetation growth and increasing shade in the riparian zone. During the period of salvage logging after the fire, nearly all sites warmed, and after salvage logging was complete, most sites did not significantly change.

During the year immediately after the fire (September through August), all the stream monitoring sites that were measured more than 10 times experienced a warming trend (after accounting for air temperature trends). Warming was measured at sites above the fire zone (DC and BCT) as well as sites whose watersheds burned. The warming likely has multiple causes, however it was greatest at sites DCH, RC, and CC (Fig. 11), which were most affected by the fire and salvage logging. No measurements were taken during the 2-week period when the fire was burning, so changes due to the fire should have been detected as a jump shift rather than a 12-month trend. Surprisingly, the only sites where an immediate shift was detected in September 2012 are Canyon Creek sites CC and CC2 (CCC was not measured). These were heavily burned, but the Rock Creek and Digger Creek sites (RC, RCP, DCH), whose drainages also burned, did not see an immediate shift. The warming trends in Canyon Creek, Rock Creek, and lower Digger Creek during the 12-month post-fire period suggests that salvage logging played an important role. All of the salvage logging occurred during this period and it appears to have included most of the riparian areas of both intermittent and perennial streams in the burn zone. Figures 26-28 show vertical Google Earth images of Digger Creek before the fire (Fig. 26), shortly after the fire (Fig. 27), and after salvage logging (Fig. 28). The fire burned very hot here, even consuming green islands within the clearcut, but left many standing dead or burned trees. The parallel lines in Figure 27 are the shadows of standing trees. The salvage logging removed all burned stems greater than 30cm in diameter at breast height (Fig. 28), and pre-emergent herbicides were applied to eliminate competition with regenerating conifer trees. Riparian areas are visible as green strips due to the exclusion of herbicides (Fig. 28).

Changes in summer temperatures (June through September) are more dramatic than during the other months. In California's Mediterranean climate, summer is the hottest and driest time of year, so flows are low and easily warmed. Again, we didn't see an immediate effect after the fire (in September 2012) except at CC and CC2, and possibly DCH. But we saw very large year-over-year changes (4-9°C) in Canyon Creek (CC), Rock Creek (RC), and Digger Creek (DCH), reflecting the combined effects of fire and salvage logging. The increases in the first year are statistically correlated with proportion of watershed burned but the effects of the fire and subsequent salvage logging are not easily separated. The post-fire warming (Figs. 10 and 11) suggests that salvage logging is important, but the upstream-downstream comparison of paired measurements on Digger Creek (Fig. 15), suggests that the full effects were realized before salvage logging was completed. Note however that this last statement is based primarily on the first 4 post-fire measurements in Digger Creek (collected in September 2012), as subsequent measurements were taken during cooler months when effects were muted. Three of the first 4 post-fire measurements at DCH do not fit the overall trend in Figure 10. Comparing the September 2012 residuals (Fig. 13) at DCH (magenta) with the September 2013 residuals (green) does suggest that salvage logging had a warming effect.

The combination of fire and salvage logging increased summer temperatures by as much as 9°C during the warmest conditions. While the statistical evidence for the specific influence of salvage logging is not absolutely clear, there is every reason to believe it should be real and the mechanism is straightforward; all those standing dead trees create shade (Fig. 27) and their removal increases direct solar radiation on the stream. Amaranthus et al. (1989) reported that 3 streams retained a mean of 30% shade after an intense wildfire consumed all crowns in most of the riparian zone of a mature Douglas-fir and hardwood forest in southern Oregon. Most of the remaining shade was from dead vegetation, which provided more than three times that from topography and two times that from live vegetation. They concluded: "Removal of dead vegetation shade from riparian zones by timber salvage or other postfire activities should be carefully considered where water temperatures reach critical levels for fish."

The warming at SFB relative to NFB could be due to a combination of factors: larger proportions burned and salvage logged, a reduction in water transfers from the North Fork, increased exports from the South Fork, and recent severe sedimentation that has filled in the pools and aggraded the lower South Fork channel. The Draft EIS (USBR and SWRCB, 2005) predicts further warming in this reach:

> Under the Restoration Project during the summer, the cooler Inskip Powerhouse flow will bypass South Fork Battle Creek via connectors, which can result in temperatures as much as 8°F warmer in the 1-mile stream segment below Coleman Dam (cooled under baseline conditions). Although the Restoration Project will not provide the cooler discharges noted as part of the baseline conditions, it will not result in a significant reduction of habitat because it will stabilize the overall temperature regime by eliminating fluctuations associated with outages.

It is implied that fluctuations associated with canal and turbine outages reduce habitat value, reducing the benefits of cooler discharges from the North Fork. Site SFB is about 1.3 km below the Coleman Dam and 2.7km above the confluence with the North Fork, and there are no tributary confluences in either reach, so it seems that warmer temperatures would be found in the entire 4km reach from the Coleman Dam to the confluence, rather than just the 1 mile stated in the Draft EIS.

It has long been known that complete removal of forest canopy, whether by fire or logging, can drastically increase summer water temperatures. For example, in the Oregon Coast range, annual maximum temperatures increased by 10°C one year after clear-cut logging that removed streamside vegetation (Brown and Krygier, 1970). In a nearby watershed where strips of vegetation were left along the perennial streams, no changes were observed that could be attributed to clearcutting. The increased temperatures in Battle Creek should decrease through time as riparian vegetation and shade levels recover , but establishment of a shade-producing canopy is likely to be slower than in wetter forest types (Moore et al., 2005). Summer maximum water temperatures showed no signs of returning to pre-fire norms 7 years after fire in the Bitterroot River basin in Montana (Mahlum et al., 2011) and remained significantly elevated at least a decade after wildfire in Idaho's Boise River basin (Dunham et al., 2007). After clear-cutting with removal of riparian vegetation in the H.J. Andrews Forest in the western Cascades, Oregon, maximum stream temperatures increased 7°C and gradually returned to preharvest levels after 15 years (Johnson and Jones, 2000).

Based on FWS Hobo temperature data, BCA daily maxima are biased high by an average 1.3°C at SFB and 2.8°C at NFB. Potential bias at the other sites limits the reliability of comparisons of Battle Creek tributary temperatures with salmonid thermal tolerances. But based upon the MWMT estimated from BCA measurements, most locations affected by the fire and salvage logging now routinely exceed 20°C, so are no longer good habitat for salmonid holding and migration during the months of June to September. Temperatures high enough to eliminate all salmonids (>22-24°C) are now common during the summer in Rock Creek, Canyon Creek, lower Digger, and the South Fork of Battle Creek. The upper Bailey Creek site, which is likely indicative of conditions between the diversion sites near the town of Viola and the spring above BCP, has many days with maxima greater than 20°C. Exposure to such temperatures would be stressful for spring-run chinook, since adults like to hold in cool water habitats through the summer, before spawning from mid-August through early October. Summer steelhead prefer even cooler temperatures than chinook. The mainstem of the North Fork, if temperatures measured at NFB are typical, is in slightly better condition than tributaries affected by the fire, possibly because less than 10% of its watershed was burned. There also may be cooler rifugia in other parts of the watershed where spring-run chinook could hold in stream reaches unaffected by the fire or where cold-water springs mitigate the fire effects. FWS measurements near NFB suggest that the North Fork remains hospitable for salmon but not steelhead. FWS measurements at SFB indicate that the South Fork is relatively inhospitable, with maximum temperatures exceeding 22°C on 28 days in 2015.

Winter-run Chinook pass into the Sacramento River from December through early August and historically have spawned in the upper reaches of tributaries from mid-April through August. Winter-run fry emigrate downstream from July through March. Even if adults were able to spawn in the spring before temperatures heated up, current conditions at any of the Battle Creek monitoring sites would be too warm (>13°C) for egg incubation and emigration, which would normally occur starting in July.

Post-fire forest management should be conducted with consideration to the fact that much of Battle Creek is now in a temperature-impaired condition. Harvesting with riparian buffers should moderate stream temperature increases and changes to riparian microclimate, but substantial warming has nevertheless been observed in many studies of harvesting near streams with both unthinned and partial retention buffers (Moore et al., 2005). Forest harvesting increases advection and sensible heat exchange from clearings to the riparian zone, and conduction between stream water and nearby soils or substrates also may be an important factor (Johnson and Jones, 2000). The magnitude of stream temperature change and the degree of influence on riparian microclimate are typically reduced as buffer width increases (Moore et al. 2005).

CONCLUSIONS

North Fork site NFB is currently the only BCA monitoring site that salmonids have access to. The Eagle Creek dam currently prevents salmonids from reaching Digger Creek and the other North Fork tributaries monitored by BCA. Because habitat in the South Fork has recently been acutely impaired by sedimentation, FWS has constructed an exclusionary weir to prevent spring Chinook salmon from entering until conditions improve. Fortunately, the North Fork has not warmed following the Ponderosa Fire, with daily maxima generally remaining below 17°C during the summer months according to FWS Hobo temperature data. June-to-September temperatures above the fire zone remain generally below 16°C in upper Digger Creek, but are warmer in upper Bailey Creek where summer flows are very low, possibly due to water withdrawals. Summer temperatures have increased by up to 9°C in Canyon Creek, Rock Creek, and Digger Creek following wildfire and salvage logging. Less dramatic warming occurred in the South Fork. As of the third summer following the fire, temperatures remain high enough in the lower reaches of these four streams to eliminate or exclude salmonids during the summer months. By the time the BCRP is completed in 2020, the Eagle Creek dam will no longer be a fish barrier and the Coleman Dam on the South Fork will have been removed. However, at this time, salmonid habitat in many of the stream reaches that would be opened up is severely degraded due to elevated water temperatures and sedimentation. Silvicultural management and WLPZ prescriptions affecting streams that flow through burned areas should give consideration to the fact that water temperatures are already elevated downstream.

Evidence is mixed regarding the relative influences of fire and salvage logging in raising water temperatures. There is little doubt that fire had an important influence, but the BCA data set suggests the influence of salvage logging after the Ponderosa fire was also considerable. Water temperature increases were limited in magnitude and spatial distribution in the first month after the fire. Standing dead and dying trees were abundant at that time, providing partial shade in streamside riparian zones and elsewhere. During the period of salvage logging, both burned and unburned sites trended warmer, but the biggest temperature increases were at sites draining watersheds that were being salvage logged: Canyon, Rock, and Digger Creeks.

Figure 26. Digger Creek, 6 weeks before the Ponderosa Fire, Jul 2012.

Figure 27. Digger Creek 3 weeks after the Ponderosa Fire, Sep 2012. Same view as Figure 26.

Figure 28. Digger Creek, after salvage logging and herbicide treatment, May 2014. Same view as Figures 26 and 27.

REFERENCES

Alley, W. M. 1988. Using exogenous variables in testing for monotonic trends in hydrologic time series. *Water Resources Research*, 24,1955-1961.

Amaranthus, Michael; Jubas, Howard; Arthur, David. 1989. Stream shading, summer streamflow and maximum water temperature following intense wildfire in headwater streams. In: Berg, Neil H., tech. coord. Proceedings of the symposium on fire and watershed management; 1988 October 26-28; Sacramento, CA. Gen. Tech. Rep. PSW-109. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station: 75-78.

Aulenbach, B. T. and Hooper, R. P. 2006. The composite method: an improved method for stream-water solute load estimation. *Hydrological Processes*, 20, 3029-3047.

Brown, G.W. and Krygier, J.T. 1970. Effects of clear-cutting on stream temperature. Water Resources Res. 6(4): 1133-1139.

Brown, Matt. 2015. Letter to Guy Chelelat (Engineering Geologise, Regional Water Quality Control Board) from Matt Brown (Fish Biologist, U.S. Fish and Wildlife Service). July 20, 2015. Viewable online at : < http://www.battle-creek.net/docs/gbcwwg/USFWS_MemoIncreaseInFneSedimentSouthForkBattleCreek_final.pdf>

Carter, K. 2005. The effects of temperature on Steelhead trout, Coho salmon, and Chinook salmon biology and function by life stage. California Regional Water Quality Control Board, North Coast Region. 26pp.

Cleveland, W. S. and Devlin, S.J. 1988. Locally-weighted regression: an approach to regression analysis by local fitting. Journal of the American Statistical Association 83: 596-610.

Dunham , J.B., Rosenberger, A.E., Luce, C.H., and Rieman, B.E. 2007. Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. Ecosystems 10: 335-346.

Johnson, J.A. and Jones, J.A. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 30–39.

Jones & Stokes. 2004. Draft action specific implementation plan, Battle Creek Salmon and Steelhead Restoration Project. (J&S 03-035). April. Sacramento, CA.

Kier Associates. 2009. Aquatic Habitat Conditions in Battle Creek and Their Relationship to Upland Management. November 2009, Kier Associates, Arcata, CA. 34pp.

Lewis, Jack. 2014. An Analysis of Turbidity in Relation to Timber Harvesting in the Battle Creek Watershed, northern California. Report prepared for the Battle Creek Alliance, Manton, CA. 28pp.

Mahlum, S.K., Eby, L.A., Young, M.K., Clancy, C.G. and Jakober, M. 2011. Effects of wildfire on stream temperatures in the Bitterroot River Basin, Montana. Int'l J. Wildland Fire 20: 240-247.

Moore, R.D., Spittlehouse, D.L., and Story, A. 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. J. American Water Resources Assoc. 813-834.

Myers, Tom. 2012. Cumulative Watershed Effects of Timber Harvest and Other Activities: Battle Creek Watershed, Northern California. July 3, 2012. Report prepared for Battle Creek Alliance, Manton, CA. Reno, NV. 52pp.

U.S. Bureau of Reclamation (USBR) and State Water Resources Control Board (SWRCB). 2005. Water Temperature and Aquatic Habitat in Battle Creek. Appendix K of Battle Creek Salmon and Steelhead Restoration Project Draft Supplemental Environmental Impact Statement/Revised Environmental Impact Report

U.S. Environmental Protection Agency (USEPA). 2003. EPA Region 10 Guidance for Pacific Northwest State and Tribal Water Quality Standards. Region 10, Seattle, WA. EPA 910-B-03-002. 49pp. Viewable online at: <http://www.epa.gov/r10earth/temperature.htm>.

Washington State Department of Ecology (WDOE). 2002. Evaluating Standards for Protecting Aquatic Life in Washington’s Surface Water Quality Standards: Temperature Criteria. Draft Discussion Paper and Literature Summary. Publication Number 00-10-070. 189pp.