Effect of contemporary forest harvesting practices on headwater stream temperatures: Initial response of the Hinkle Creek catchment, Pacific Northwest, USA

Kelly M. Kibler, Arne Skaugset, Lisa M. Ganio, Manuela M. Huso

Department of Forest Engineering, Resources, and Management, Oregon State University, 270 Peavy Hall, Corvallis, Oregon 97331, USA
Department of Forest Ecosystems and Society, Oregon State University, 321 Richardson Hall, Corvallis, Oregon 97331, USA

1. Introduction

Stream temperature is a first-order control of aquatic productivity, regulating oxygen solubility, organic matter decomposition and nutrient cycling within the stream ecosystem (Weatherley and Gill, 1995; Ice, 2008), as well as metabolism and growth of aquatic organisms (Phinney and McIntire, 1965; Marr, 1966; Brett et al., 1969; Brett, 1971). Changes to prevailing thermal regimes stimulate physiological and behavioral response mechanisms in aquatic biota. For example, physiological stress and mortality (Brett, 1952; Moring and Lantz, 1975), and changes in growth rates, fecundity, trophic structure, competitive interactions, and timing of life history events (Brett, 1971; Sweeney and Vannote, 1978; Beschta et al., 1987; Hogg and Williams, 1996) are observed in communities of aquatic organisms exposed to changes in ambient water temperature. In extreme cases, changes to thermal characteristics may alter the stream environment to the extent that native species are extirpated from historic habitats. Pacific salmonids, cold-water fishes with an acute thermal tolerance of approximately 25 °C, inhabit freshwater streams during many stages of life history, and are thus particularly vulnerable to stream temperature increases (Brett, 1952).

Many interacting processes and mechanisms contribute to stream temperature patterns; however, energy budget analysis indicates that exposure to solar radiation is the primary temperature determinant in small, shallow streams (Brown, 1969; Johnson, 2004; Moore et al., 2005). In forested ecosystems of the Pacific Northwest, solar radiation exposure is limited by shading from the forest canopy. Extreme increases in reach-level stream temperatures are often observed when forest canopies are removed (Lehno and Rothacher, 1967; Brown and Krygier, 1970; Swift and...
streams during harvesting. However, where stream buffers consisting of mature timber are maintained, preserving some percentage of pre-harvest canopy closure, investigators do not observe significant changes to stream temperature (Macdonald et al., 2003; Gomi et al., 2006). In the absence of shading provided by mature timber, there is some evidence that logging slash (coarse and fine woody and vegetative debris left after forest harvesting) may function as an agent of post-harvest shade, with potentially mitigating effects to temperatures of streams partially or fully covered by slash. For instance, Jackson et al. (2001) attributed a damped post-harvest temperature response of clearcut streams to exclusion of solar radiation due to a layer of logging slash that deposited over streams during harvesting.

A key focus of contemporary watershed management is the role of cumulative watershed effects from the summation of many seemingly benign individual activities that produce a significant additive effect (Beschta and Taylor, 1988). Forest practice regulations do not require retention of buffer strips comprised of overstory conifers around small, non-fish-bearing streams in some regions of Oregon. There is concern that reach-level stream temperature increases resulting from exposure of small, unbuffered streams may propagate into cumulative watershed effects that affect downstream salmonid habitats (Reid, 1998). In order to assess the likelihood of cumulative watershed effect, it is important to consider processes of stream thermal dynamics operating at the reach scale. Considerable research has focused on stream temperature effects of forest harvesting, however, much historic research occurred during the era of old growth conversion, using equipment and techniques that have been replaced by modern practices and before the current suite of forest practice rules were put into place. An investigation of the effects of timber harvest on stream temperatures undertaken on privately owned, intensively managed forest land with young, harvest-regenerated forest stands harvested using contemporary forest practices is necessary to assess the potential reach-level and watershed-scale stream temperature impacts of contemporary forest practices. The objectives of this study are threefold: (1) quantify summer stream temperature changes in four small, non-fish-bearing streams at the downstream boundary of clearcut harvest units the first summer after timber harvest; (2) quantify changes in canopy closure that resulted as a consequence of contemporary forest practices; and (3) investigate changes in stream temperature at the watershed outlet to discern the watershed-scale cumulative effect of harvesting multiple small, non-fish-bearing headwater streams.

2. Methods

2.1. Study design and location

We conducted this study as a part of the Hinkle Creek Paired Watershed Study (HCPWS). The HCPWS is a nested, paired watersheds study located in southern Oregon approximately 40 km northeast of Roseburg, Oregon. The study area (Fig. 1), comprising the headwaters of Hinkle Creek, contains two fourth-order watersheds: a reference watershed, North Fork Hinkle Creek (NFH), and a treatment watershed, South Fork Hinkle Creek (SFH). Within these fourth-order watersheds, we selected six headwater (first order) catchments for detailed study (Table 1). Areas of four small catchments located in the SFH watershed, named Fenton, Clay, Russell, and BB, were harvested during this study. As the experimental units of this study, we refer to these four small catchments as the “treatment” catchments (t). The remaining two small catchments, named Myers and DeMerrsseman, are located in the NFH watershed and remain undisturbed through the extent of this study. We thus refer to these two small catchments as the “reference” catchments (r).

Hinkle Creek, a tributary to Calapooya Creek in the Umpqua River basin, is located in the foothills of the western Cascades in southern Oregon. The study area ranges in elevation from 400 m above sea level at the mouth of the watershed to approximately 1250 m above sea level. Average annual precipitation ranges from 1400 mm at the mouth of the watershed to 1900 mm at the watershed divide. The geology of the Hinkle Creek watershed is comprised of rhyolite and basalt flows; soils derived from these parent materials are clay loams to silty clay loams and are classified as a Typic Palehuma or a Typic Haplumbrept. The study watersheds support a forest stand composed predominately of 60-year-old, harvest-regenerated Douglas-fir (Pseudotsuga menziesii) with minor components of western hemlock (Tsuga heterophylla) and western redcedar (Thuja plicata). The riparian stand is made up of the aforementioned conifers and red alder (Alnus rubra), with sword fern (Polystichum munitum) and huckleberry (Vaccinium parvifolium) in the understory. Resident cutthroat trout (Oncorhynchus clarki clarki) are the most abundant salmonids in fish-bearing reaches of the study watershed. Roseburg Forest Products owns virtually the entire study watershed, which is actively managed for the production of solid wood.

2.2. Harvesting treatment

We initiated the HCPWS in fall 2002. In 2001, prior to the initiation of the HCPWS, forest managers had harvested timber from 119 ha or 11% of the SFH (t) watershed in three clearcut harvest units (Fig. 1). We collected pre-harvest data from autumn of 2002 to autumn of 2005. The experimental harvest entry, consisting of five clearcut harvest units located in the small treatment catchments of the SFH (Fig. 1), took place between August 2005 and May 2006. We continued collection of post-harvest data through autumn of 2006. The experimental harvest units were located adjacent to non-fish-bearing streams. Timber harvest proceeded in accordance with current Oregon Forest Practice Rules, which do not require retention of fixed-width buffer strips adjacent to non-fish-bearing streams. Thus, as a part of the harvest activities, fixed-width buffer strips containing merchantable overstory conifers were not left adjacent to the non-fish-bearing streams.

Roseburg Forest Products harvested portions of the experimental catchments using a clearcut silvicultural system. Trees were felled by hand and yarded to landings with a slackline, skyline cable system with a motorized, slack-pulling carriage. This yarding system allowed trees in the vicinity of streams to be elevated above the ground and transported fully suspended to the landing. Site preparation activities occurred in the clearcuts throughout the spring, summer, and autumn of 2006. These activities included piling and burning of logging slash, concentrated in the vicinity of the landings, and aerial application of herbicides. The clearcuts were replanted with Douglas-fir seedlings during the winter of 2006–2007.

2.3. Data collection

We measured stream flow and temperature in eight locations of the Hinkle Creek basin: at the outlets of the two fourth-order watersheds (NFH (r) and SFH (t)) and in each of the six small catchments. The United States Geological Survey (USGS) gauged stream discharge at the outlets of the NFH and SFH using current meter sections. We installed discharge gauging stations with Montana flumes (Tracom, Montana Flume) in the six small, non-fish-bearing streams at or near the transition from a fish-bearing to non-fish-bearing designation, which coincided with the downstream boundary of clearcut harvest units.
We observed warm-season stream temperatures in these eight locations over a four-year pre-harvest period (2002 through 2005) and for one year following the harvest (2006). From 2002 to 2003, we recorded stream temperature using calibrated Vemco 12 bit Minlog data loggers (±0.2 °C accuracy) at 10–30 min intervals. From 2004 to 2006, we measured and recorded stream temperature every 10 min with calibrated HOBO Water Temp Pro data loggers (Onset HOBO model H20-001, ±0.2 °C accuracy). We deployed calibrated thermistors in the late spring or early summer of each year and recorded stream temperature data continuously until the late autumn. We placed thermistors in the same locations each year, in the vicinity of discharge-gauging equipment (Fig. 1). To avoid erroneous temperature data caused by direct solar radiation, we placed the thermistors in covers of white PVC piping.

<table>
<thead>
<tr>
<th></th>
<th>Area (ha)</th>
<th>Area harvested (ha)</th>
<th>Area harvested (%)</th>
<th>Stream length (m)</th>
<th>Stream length harvested (m)</th>
<th>Stream length harvested (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatment streams</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fenton</td>
<td>23</td>
<td>15</td>
<td>65</td>
<td>900</td>
<td>620</td>
<td>69</td>
</tr>
<tr>
<td>Clay</td>
<td>65</td>
<td>25</td>
<td>38</td>
<td>2040</td>
<td>780</td>
<td>38</td>
</tr>
<tr>
<td>Russell</td>
<td>96</td>
<td>12</td>
<td>10</td>
<td>1800</td>
<td>630</td>
<td>35</td>
</tr>
<tr>
<td>BB</td>
<td>111</td>
<td>34</td>
<td>31</td>
<td>2280</td>
<td>1060</td>
<td>46</td>
</tr>
<tr>
<td>SFH</td>
<td>1084</td>
<td>154</td>
<td>14</td>
<td>25,653</td>
<td>4544</td>
<td>18</td>
</tr>
<tr>
<td><strong>Reference streams</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Myers</td>
<td>86</td>
<td>–</td>
<td>–</td>
<td>2100</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>DeMersseman</td>
<td>160</td>
<td>–</td>
<td>–</td>
<td>1580</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>NFH</td>
<td>856</td>
<td>–</td>
<td>–</td>
<td>21,405</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 1. Hinkle Creek study catchments. Black points represent approximate locations of temperature data loggers, flumes, transition points between fish-bearing and non-fish-bearing streams and the downstream extent of timber harvest in treatment streams. Stream reaches surveyed for canopy closure in 2004 and 2006 are also shown.

Table 1 Watershed areas and stream lengths of reference and treatment catchments in the Hinkle Creek Paired Watershed Study. Areas of harvested catchment are shown in hectares (ha) and as percent of total catchment area; harvested stream length is given in meters and as percent of total catchment stream length.
To ensure that water flowed freely into the PVC piping and over the thermistors, we drilled several holes in the covers and oriented the thermistors along stream flow lines. In addition to deploying these warm-season thermistors, we collected stream temperature data throughout the year within 10 m of each warm-season thermistor. We measured and recorded 30-min stream temperature data at stream gauging stations as a part of specific conductance measurement (Campbell Scientific CS547A conductivity sensors, ±0.1 °C accuracy). We relied on data collected by conductivity sensors as a backup in case a thermistor should disappear, and also compared the two data sources for quality assurance.

We measured canopy closure (the proportion of sky covered by vegetation that attenuates solar radiation, as defined by Jennings et al., 1999) over the treatment and reference streams during the summer of 2004 and repeated canopy closure surveys during the summer of 2006. We measured canopy closure at sample plot locations spaced at 10-m intervals along the stream after starting with a random interval within the first 10 m. In the four treatment streams, we measured canopy closure from 300 m downstream of gauging stations to the upstream extent of the clearcuts (Fig. 1). In the two reference streams, we measured canopy closure at 10-m intervals from 300 m downstream of gauging stations to at least 400 m upstream of gauging stations (Fig. 1).

In 2004, we measured percent canopy closure using spherical densiometers held at waist height. At each sample location, we took four measurements of canopy closure: once facing upstream, once facing downstream, once facing river right, and once facing river left. We then computed mean canopy closure at each sample location from these four independent estimates, as well as reach-level canopy closure.

We repeated the survey of percent canopy closure in 2006. Again, we measured canopy closure every 10 m along each of the six streams after a random start. We measured canopy closure with spherical densiometers using the methods described above. However, the spherical densiometer held at waist height did not adequately characterize canopy closure provided by material located between the stream surface and waist height. Thus, we used digital photographs to assess canopy closure provided by material below waist height. We took a digital photograph at each sampling location from a height of 6 in. above the water surface and orthogonal to the stream surface. We placed the camera at the center of the stream, in the same location that we collected densiometer data. A bubble level attached to the camera ensured that the camera was level and the photograph sampled an area directly above the stream. We analyzed digital photographs with Adobe Photoshop 7.0 software, classifying light and dark pixels and quantifying the proportion of each to determine canopy closure at each location.

2.4. Data analysis

2.4.1. Maximum, minimum, and mean daily stream temperatures

The HCPWS is a nested, paired watershed study with a BACI study design. We paired treatment and reference catchments based on similarity in catchment area, aspect, stream orientation, stream length, and discharge, resulting in the following pairs of treatment-reference streams: Fenton–Myers, Clay–Myers, Russell–DeMerrseman, BB–DeMerrseman, and SFH–NFH. We extracted daily maximum, mean, and minimum stream temperatures for all thermistor locations, all years. Analysis of stream temperature parameters on a daily time step indicated that temperature values separated by intervals of at least three days were not significantly correlated. Thus, to avoid serial autocorrelation and ensure independence of our data, we selected a data set including maximum, mean, and minimum daily stream temperature for every third day, after a random start on the 1st, 2nd, or 3rd day of the summer.

We fit daily stream temperature parameters for each year and each stream pair with a least squares linear regression representing the relationship between temperatures of each treatment and reference stream for a given year. The result is five regression lines each for the Myers–Fenton, Myers–Clay, DeMerrseman–BB, and NFH–SFH watersheds paired, corresponding to five years of data collection: four pre-harvest regression lines and one post-harvest regression line. The DeMerrseman–Russell watershed pair is missing one year of data (2002) due to equipment malfunction, and thus has four regression lines; three pre-harvest and one post-harvest. We then extracted slope and intercept parameters from regression equations for each stream pair, each year.

We normalized temperature data from reference streams by subtracting the mean value of the annual mean daily temperature from each daily value. This adjustment repositions the x-axes of reference-treatment regression plots such that the intercept coefficient of each regression line corresponds to a meaningful value: the temperature of the treatment stream when the mean daily temperature is observed in the reference stream. This adjustment facilitates intuitive interpretation of intercept data, and we normalize reference stream data in this way for maximum, mean, and minimum stream temperatures.

We performed analysis of variance (ANOVA) using SAS software (version 9.1, SAS Corporation, Cary, NC) on slope and intercept parameters derived from reference-treatment regression plots, with year as a fixed effect and stream as a random effect (Meredith and Stehman, 1991; Loftis et al., 2001). We assessed the effect of treatment on each coefficient with a single degree of freedom contrast of average pre-treatment years versus the single post-treatment year. We performed similar analyses of least squares regression parameters to detect changes in daily maximum, minimum, and mean summer stream temperatures at two scales: at the catchment scale in four small headwater streams adjacent to harvest units, and at the watershed scale at the mouth of SFH (t), downstream of the headwater harvest units.

The stream temperature data analyzed in this study are structured hierarchically in time and space. Temporally, the stream temperature measurements are repeated on a daily and annual scale and include pre-harvest and post-harvest years. Spatially, the four treatment streams and two reference streams represent individual catchments, but they are also nested within the Hinkle Creek watershed, which is represented by data the mouth of the South Fork (t) and North Fork (r) of Hinkle Creek. Traditional statistical analyses does not adequately address this hierarchy in the data structure (Bryk and Raudenbush, 1992), thus we developed a hierarchical linear model to identify and quantify the sources of variation in the data and to isolate the variability at each level of the hierarchy of the stream temperature data. We fit a two-level random coefficients model to the daily maximum, mean, and minimum stream temperature data (Singer, 1998), which we term the watershed-scale model. At the first level of the watershed scale model, we plot values of daily maximum, mean, and minimum stream temperature for each stream pair and fit least squares regression to the data. At the second level of the hierarchy, we model the intercept and slope of the regression lines as random effects after accounting for the fixed effect of timber harvesting on these parameters. The watershed-scale model takes the form:

\[
\begin{align*}
t_{\text{max}} & = a_{\text{max}} + b_{\text{int}} + e_{\text{int}} \\
\beta_{\text{bth}} & = x_{00} + x_{01} \cdot lct_{\text{bth}} + \delta_{\text{bth}} \\
\beta_{\text{rth}} & = x_{10} + x_{11} \cdot lct_{\text{rth}} + \delta_{\text{rth}}
\end{align*}
\]
where \( \epsilon_{ij} \sim N(0, \sigma^2) \) and \( \text{COV}(\epsilon_{ij}, \epsilon_{ik}) = 0 \) and
\[
\left( \frac{\epsilon_{ij}}{\epsilon_{ik}} \right) \sim \text{MVN}\left( \frac{0}{0}, \frac{\sigma_{00} \sigma_{01}}{\sigma_{10} \sigma_{11}} \right)
\]
therefore
\[
t_{\max ij} = \alpha_{00} + \alpha_{01} \times I_{\text{cut} h} + \delta_{00} + (\alpha_{10} + \alpha_{11} \times I_{\text{cut} h} + \delta_{10})
\]
\[
\times r_{\max ij} + \epsilon_{ij}
\]
\[
t_{\max ij} = \alpha_{00} + \alpha_{01} \times I_{\text{cut} h} + \alpha_{10} + r_{\max ij} + \alpha_{11} \times r_{\max ij} + \delta_{00} + \delta_{10} + \delta_{11} + r_{\max ij} + \epsilon_{ij}
\]
where \( t_{\max ij} \) is the maximum, mean, or minimum stream temperature for day \( j \), in year \( i \), in treatment stream \( h \); \( r_{\max ij} \) is the maximum, mean, or minimum stream temperature recorded on day \( j \), in year \( i \), in reference stream \( h \); \( h \) is Fenton (t), Clay (t), Russell (t), BB (t), Myers (t), or DeMerrseman (t); \( i \) is 2002, 2003, 2004, 2005, 2006; and \( j \) is 1, 2, \ldots, \( n_{hi} \) ~ 33.

### 2.4.2. Canopy closure

We calculated mean percentages of canopy closure and standard deviation from data collected at sample plot locations upstream (US) or downstream (DS) of gauging stations on each of the treatment and reference streams. We assessed the magnitude of variability attributable to different field crews and years by evaluating differences in mean canopy closure between pre-harvest (2004) and post-harvest (2006) years in stream reaches where timber harvest did not occur (Myers US, Myers DS, DeMerrseman US, DeMerrseman DS, Fenton DS, Russell DS and BB DS). Timber along the downstream reach of Clay Creek (t) had been harvested in 2001, before the implementation of this study. Thus, the canopy closure data for the Clay DS reach do not represent a condition that closure data for the Clay DS reach do not represent a condition that

### 3. Results

#### 3.1. Stream temperature

Providing a thermal context for research results, Table 2 summarizes temperature data from all streams and years. The relationship between watershed size and stream temperature is evident when we compare temperatures from NFH (t) and SFH (t) to those observed in headwater streams (Table 2). The maximum stream temperature recorded in SFH (t) throughout the duration of the study is 19.2 °C (2003). Before timber harvest, the maximum temperature recorded in SFH (t) is 18.4 °C (2003), while a maximum temperature of 18.7 °C is recorded in SFH (t) after harvest, in 2006.

#### 3.1.1. Catchment-scale temperature changes

Stream temperatures in treatment and reference headwater streams exhibit strong correlation, both before and after timber harvest. Adjusted correlation coefficients for all stream pairs, all years range from 0.89 to 0.99, with a mean of 0.97 (Figs. 2 and 3). In treatment streams, post-harvest annual maximum temperatures (the highest temperature recorded in a given year) and mean maximum daily temperatures (the maximum temperature recorded each day, averaged over the warm season) differ from values averaged over pre-harvest years, though the direction of differences is inconsistent among headwater streams. The annual maximum temperature of Fenton Creek (t) in 2006 (the first summer following harvest) is 2.1 °C lower than the average of the four pre-harvest years, while the mean maximum daily temperature for 2006 is 1.6 °C lower than pre-harvest years. In BB Creek (t), Clay Creek (t), and Russell Creek (t), annual maximum temperatures in 2006 are 0.5 °C to 1.1 °C warmer than the mean of pre-harvest years, while mean maximum daily temperatures are 0.6 °C to 1.1 °C warmer than pre-harvest years.

We detect significant differences in pre- and post-harvest relationships (intercept and/or slope parameters) between maximum daily stream temperatures of treatment and reference non-fish-bearing headwater streams (Table 3a). We also detect significant differences in slopes and intercepts of pre- and post-harvest slopes for the Clay–Myers and Russell–DeMerrseman stream pairs (\( p = 0.916 \) and \( p = 0.875 \), respectively); however, post-harvest intercepts are significantly greater (\( p < 0.001 \)) than those of the pre-harvest relationship (Fig. 2a). With regard to the BB–DeMerrseman stream pair, the slope and intercept of the post-harvest regression relationship are significantly greater (\( p < 0.001 \)) than those describing the pre-treatment regression relationship (Fig. 2d). Finally, we do not detect significant changes between pre- and post-harvest temperatures observed in headwater streams (Table 2). The maximum stream temperature recorded in NFH (t) throughout the duration of the study is 19.2 °C (2003). Before timber harvest, the maximum temperature recorded in SFH (t) is 18.4 °C (2003), while a maximum temperature of 18.7 °C is recorded in SFH (t) after harvest, in 2006.

### Table 2

The (a) maximum and (b) minimum stream temperatures (°C) observed in all locations for summers 2002–2006. The shaded values indicate data collected after timber harvest.

<table>
<thead>
<tr>
<th>Stream</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Maximum stream temperature (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Myers</td>
<td>15.4</td>
<td>16.2</td>
<td>15.2</td>
<td>14.9</td>
<td>16.6</td>
</tr>
<tr>
<td>DeMerrseman</td>
<td>14.5</td>
<td>14.6</td>
<td>14.5</td>
<td>14.4</td>
<td>15.3</td>
</tr>
<tr>
<td>NFH</td>
<td>17.5</td>
<td>19.2</td>
<td>17.5</td>
<td>17.5</td>
<td>18.7</td>
</tr>
<tr>
<td>Fenton</td>
<td>15.1</td>
<td>16.2</td>
<td>16.1</td>
<td>14.2</td>
<td>14.5</td>
</tr>
<tr>
<td>Clay</td>
<td>16.8</td>
<td>16.3</td>
<td>16.8</td>
<td>15.4</td>
<td>19.7</td>
</tr>
<tr>
<td>Russell</td>
<td>16.3</td>
<td>14.8</td>
<td>13.9</td>
<td>14.0</td>
<td>16.0</td>
</tr>
<tr>
<td>BB</td>
<td>14.8</td>
<td>15.5</td>
<td>14.8</td>
<td>14.6</td>
<td>16.2</td>
</tr>
<tr>
<td>SFH</td>
<td>16.9</td>
<td>18.4</td>
<td>17.5</td>
<td>17.3</td>
<td>18.2</td>
</tr>
<tr>
<td>(b) Minimum stream temperatures (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Myers</td>
<td>10.8</td>
<td>10.0</td>
<td>10.8</td>
<td>11.2</td>
<td>10.9</td>
</tr>
<tr>
<td>DeMerrseman</td>
<td>10.8</td>
<td>10.3</td>
<td>10.6</td>
<td>11.2</td>
<td>10.8</td>
</tr>
<tr>
<td>NFH</td>
<td>9.9</td>
<td>9.8</td>
<td>10.2</td>
<td>10.7</td>
<td>8.1</td>
</tr>
<tr>
<td>Fenton</td>
<td>10.1</td>
<td>11.6</td>
<td>12.1</td>
<td>10.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Clay</td>
<td>10.2</td>
<td>11.6</td>
<td>11.9</td>
<td>10.2</td>
<td>10.3</td>
</tr>
<tr>
<td>Russell</td>
<td>10.1</td>
<td>9.8</td>
<td>9.8</td>
<td>10.1</td>
<td>9.3</td>
</tr>
<tr>
<td>BB</td>
<td>10.8</td>
<td>10.5</td>
<td>10.5</td>
<td>10.7</td>
<td>10.8</td>
</tr>
<tr>
<td>SFH</td>
<td>10.2</td>
<td>10.1</td>
<td>9.9</td>
<td>10.8</td>
<td>8.1</td>
</tr>
</tbody>
</table>

#### Table 3a

We detect significant differences in slopes and intercepts of pre- and post-harvest relationships between maximum daily stream temperatures of treatment and reference non-fish-bearing headwater streams (Table 3a). In all cases where significant change to minimum daily temperature is detected, we observe a decreased slope and/or intercept in post-harvest regressions (Fig. 3). Across the range of temperatures observed, these changes to regression relationships indicate that minimum daily stream temperatures decreased. The decrease in slope indicates that minimum temperatures are particularly low on days when high minimum temperatures are observed in reference streams. In Fenton Creek (t), the mean minimum temperature across the 2006 warm season decreased 1.9 °C relative to pre-harvest years, and the minimum temperature on the warmest day of 2006 decreased by 2.8 °C relative to pre-harvest years.
To collectively describe temperature changes observed in individual streams, we also analyze mean change observed across the four headwater catchments. When we compare slopes and intercepts of the pre- and post-harvest regression relationships, averaged across years and catchments, we observe no detectable changes to slopes or intercepts of maximum stream temperatures (Table 4 and Fig. 5a) or to intercepts of mean and minimum temperatures (Table 4 and Fig. 5b). However, we do observe significant changes to slopes of post-harvest regression relationships describing mean ($p = 0.002$) and minimum ($p < 0.001$) daily temperatures (Table 4). In both cases, the slopes of post-harvest regression relationships decrease significantly, indicating lower mean and minimum daily temperatures downstream of all four harvest units following harvesting.

Further, a random-effects watershed-scale model including data from all four streams indicates that most (67%) variation in maximum temperatures observed in the four harvested streams is due to daily variation within individual streams, while the remainder is due to variability between streams and years. Accounting for the fixed effect of temperature observed in paired reference streams accounts for 91% of within-stream variation.

Regression parameters (slopes and intercepts) of relationships between maximum temperatures in harvested and reference streams are variable, indicating that maximum temperatures in harvested streams differ among streams and years, even after controlling for the effect of temperature in the paired reference stream. Forty-seven percent of the residual variance of maximum daily temperature in treatment streams that is controlled by the fixed relationship of maximum daily temperature in the reference streams is explained by allowing the slopes and intercepts of regression relationships to vary by stream and by year. By contrast, a small amount of random variation among slopes (6%) and intercepts (7%) is explained by the fixed effect of timber harvest, indicating the inconsistency of the timber harvest effect to maximum stream temperatures among the four harvested streams.

Analyses of watershed-scale models of mean and minimum daily stream temperatures indicate patterns of variation that are similar to those of maximum temperatures. Sixty-nine and 67% of the variation in respective mean and minimum stream temperatures of harvested streams is due to day-to-day variation within streams, whereas 31% and 33% of the total variation in mean and minimum stream temperatures, respectively, is explained by variation between streams and years. Ninety-four and 93% of the within-stream variation in mean and minimum stream temperatures, respectively, is explained when the model accounts for the fixed effect of mean and minimum temperatures in paired reference streams. The random effects of stream and year are strong in the slope and intercept regression parameters of mean and minimum stream temperatures. Sixty-three and 60% of the variance in residuals of respective mean and minimum stream temperatures controlled by the fixed relationship of temperature in the paired reference streams is explained by allowing slopes and intercepts of regression lines to vary by stream and by year. Again, only three and eight percent of the respective variation among intercepts of

---

**Fig. 2.** Maximum daily stream temperature (°C) observed in the four treatment streams and their respective reference streams: (a) Fenton–Meyers, (b) Clay–Meyers, (c) Russell–DeMersseman, and (d) BB–DeMersseman. The graphs show independent maximum daily temperatures and regression relationships for pre-harvest years (2002–2005) and one post-harvest year (2006).
mean and minimum stream temperatures is explained by the fixed effect of timber harvest. However, 15% and 26% of the variation among slopes of mean and minimum temperatures is explained by timber harvest, suggesting that the significantly lower slopes observed across all four harvested streams in the post-harvest year are due in part to timber harvest.

3.1.2. Watershed-scale temperature changes

Finally, in addition to analyzing changes observed in headwater streams just downstream of the experimental harvest units, we also investigate stream temperature changes further downstream, using data observed at the outlets of the two large study watersheds, the NFH (\(r\)) and the SFH (\(t\)) (Fig. 1). At the outlet SFH (\(t\)), we detect no significant changes to regression parameters describing pre- and post-harvest relationships for maximum, mean, or minimum daily stream temperatures (Table 3a–c and Fig. 4).

3.2. Canopy closure

We assume that canopy closure within reference reaches changed only negligibly between spherical densiometer measurements that took place in 2004 and 2006; therefore we assess any differences as measurement error related to different field crews. On average, the 2004 field crew measured four percent greater canopy closure than the 2006 field crew. A similar comparison between the 2004 and 2006 spherical densiometer data and the 2006 digital photograph data revealed, on average, that the 2004 and 2006 densiometer surveys measured respectively 13 and nine percent greater canopy closure than the 2006 digital photograph method. These differences between crews and methods represent a measure of the error between the three datasets. When this uncertainty is accounted for, canopy closure measurements may be compared across years and methods.

The average pre-harvest canopy closure for all six of the non-fish-bearing streams was 86%. This value is based on the 2004 spherical densiometer data and is corrected for crew and method (Table 5). The average pre-harvest canopy closure for the four treatment streams was also 86%. The average post-harvest canopy closure for the four treatment streams was 66% (Table 5). This value is based on the 2006 digital photo data, corrected for the effect of crew and method. Thus, on average across the four treatment streams, timber harvest reduced canopy closure above the streams by approximately 20%.

In contrast, when the pre-harvest and post-harvest spherical densiometer measurements are compared after correcting for differences in crews, the reduction in canopy closure due to timber harvest is 84%. Thus, much canopy closure over treatment streams after timber harvest was provided by material located between the height of the densiometer measurements (waist height) and the height of the digital photos (6 in. above the stream surface).

The observed reduction in canopy closure does vary across streams. The reduction in canopy closure ranges from a low of four...
percent at Fenton (t) to a high of 29% for BB (t) (Table 5). We observed reductions in canopy closure of 25% and 22% at Clay (t) and Russell (t), respectively. Further, though reach-level mean canopy closure did not change as much as expected, the spatial variability of canopy closure along each stream changed markedly after harvest. Before harvest, we observed maximum variability between individual canopy closure measurements on the order of three percent. After harvest, sequential measurements of canopy cover varied between 25% and 38%, with a mean of 34%. Before harvest, canopy closure was uniformly distributed along the stream, whereas the post-harvest distribution of canopy closure was patchy.

4. Discussion

4.1. Change observed in individual streams

Timber harvest adjacent to four non-fish-bearing streams resulted in statistically significant effects to stream temperatures observed the first summer after harvest. Maximum daily
temperatures such as those observed in Clay (t), Russell (t), and BB (t) Creeks; however we did anticipate that the temperature increases would be of greater magnitude. Maximum daily stream temperatures increased by as much as 10°C in the Alsea Watershed Study in the Oregon Coast Range (Brown and Krygier, 1970) and 7°C in the H.J. Andrews Experimental Forest in the Oregon Cascades (Levno and Rothacher, 1967, 1969; Johnson and Jones, 2000) after riparian conifers were harvested and logging slash was burned. The lack of dramatic increase in maximum daily temperature observed may be explained, at least in part, by shade provided by logging slash deposited over the streams. After harvest, shade provided to the stream by the overstory canopy was effectively removed, as indicated by the post-harvest measurements of canopy closure made with the canopy densiometer. However, when canopy closure was measured at the level of the water surface with a digital camera, the reduction in canopy closure compared with pre-harvest conditions was far less. The moderate changes in canopy closure observed in Clay (t), Russell (t), and BB (t) Creek are perhaps in line with the modest increases in daily maximum temperatures observed.

While unanticipated shading by logging slash may partially explain why increases in maximum stream temperatures are more subtle than expected, shading does little to explain why maximum daily temperatures in Fenton Creek (t) decreased following timber harvest. Post-harvest observations at Fenton Creek (t) may be explained by examining another component of the stream energy balance, the volume of summer baseflows. Harvest of forested watersheds may result in short-term increases to baseflows (Harr and Krygier, 1972; Keppeler and Ziemer, 1990; Stednick, 2008). Of the four treatment catchments, the greatest proportion of catchment area, 65%, was harvested from Fenton (Table 1). Analysis of baseflows observed during the study period indicates that baseflows increased significantly in each of the four treatment streams, as well as at the watershed outlet, following harvesting (Surfleet and Skaugset, 2013). Brown (1969) and Brown and Krygier (1970) indicate that energy required to raise stream temperature increases with discharge. Given that canopy closure over Fenton (t) did not change appreciably after harvesting (Table 5) and that summer baseflows did increase substantially, the low maximum stream temperatures observed in Fenton Creek are coherent.

With respect to minimum daily temperatures, timber harvest significantly affected relationships between treatment and reference streams. In each stream, slopes of minimum regression relationships decreased significantly following harvest. The decrease in slope was often accompanied by a significant change of intercept, with almost all intercepts related to minimum temperatures decreasing significantly. The primary effect of these changes across the range of temperatures observed was that minimum stream temperatures decreased after harvest. As explained by the lower slopes, we observe the greatest decreases to minimum temperatures on days when high minimum temperatures are observed in reference streams. The response of minimum stream temperatures to timber harvest is not studied as thoroughly as maximum stream temperature response, and research results that are available are equivocal. However, some studies do report decreases in minimum stream temperature (Beschta et al., 1987; Johnson and Jones, 2000; Moore et al., 2005; MacDonald et al., 2003), corroborating observations of this study.

### 4.2. Change averaged over individual streams

In addition to analyzing changes observed in each individual stream, we also evaluate collective response averaged over the four treatment streams (Fig. 5a and b). With respect to maximum daily temperature, we detect no statistically significant changes when data from the four streams are averaged. This result is predictable,
as the impacts to maximum temperatures detected at the scale of the individual stream consisted of muted (Russell and BB) and variable (Clay and Fenton) responses that, when averaged, balance each other such that the net effect is undetectable. However, examination of the individual catchment responses provides a more nuanced and accurate portrayal of the variable maximum temperature responses observed. When mean and minimum temperature responses are similarly averaged over the four streams, we observe statistically significant changes to slopes, but not to intercepts, of pre- and post-harvest regression relationships. These reduced slopes indicate that, across the range of temperatures observed, on days where warm mean and minimum temperatures are observed in reference streams, mean and minimum temperatures were cooler following harvest.

4.3. Change observed at the watershed scale

We detect no statistically significant impacts of timber harvest to maximum, mean or minimum daily stream temperatures observed at the SFH (t) watershed outlet. Given the muted and variable maximum temperature response in the four treatment streams draining to this common outlet, it is not surprising that we do not observe significant changes to downstream maximum stream temperatures. However, despite observing a clear signal of significantly lower minimum temperatures in all four treatment streams, we are unable to detect this signal downstream at the watershed outlet. Similar to stream temperature observations made in the Hubbard Brook experiment (Burton and Likens, 1973), we observe that thermal regimes altered by harvesting in headwater streams are either able to recover before reaching the watershed outlet, or that the changes observed are not of sufficient magnitude to allow expression at the watershed scale. This is the first time that the cumulative impact of multiple iterations of timber harvest on stream temperature has been investigated at a watershed scale. Previous stream temperature research often focuses on the impact of timber harvest on the scale of the individual stream reach or headwater watershed (Gomi et al., 2006; Groom et al., 2011; Janisch et al., 2012). In the South Fork Hinkle Creek watershed, we replicated a timber harvest treatment across the landscape and evaluated the stream temperature impact of harvesting both at the scale of individual streams as well as downstream at the watershed outlet. Analysis of stream temperature data observed at the watershed outlet indicates that, despite significant changes observed within individual streams, the

![Fig. 5](image-url)
cumulative impact of multiple, spatially-distributed timber harvest units to stream temperature was negligible at the watershed scale.

4.4. Interpreting analysis of regression parameters

We detected stream temperature effects by evaluating change in pre- and post-harvest regression relationships between temperatures gauged in treatment and reference streams (e.g. Fig. 2a–d). As this method allows visualization of temperature responses across the range of temperatures observed and thus encompasses variability of maximum, mean, and minimum daily temperatures observed, this method is superior to reductionist approaches such as comparison of means. Relationships between temperatures gauged in treatment and reference streams are defined by slope and intercept parameters of regression lines. These regression parameters impart information about how each treatment stream receives and responds to thermal stimulation relative to its reference counterpart. A change in slope or intercept between years within a given stream pair signifies that at least one stream is receiving or processing energy differently than in previous years. However, it is not to be assumed that an increase in slope or intercept implies across-the-board increase in stream temperature. A change to the intercept parameter alone signifies that every observation in the treatment stream has shifted up or down relative to its position in previous years, and that the response remains consistent across the range of observed temperatures. For instance, after harvesting we detect a significant increase in the intercept of the Clay-Myers stream pair, and no change to slope. The increase in intercept, in absence of a slope change, signifies that maximum daily temperatures increased after harvesting, and that increases of similar magnitude occurred across the range of observed temperatures.

When slopes change, this indicates that temperatures have changed inconsistently across the range of observed data. Unlike an increase in intercept, an increase in slope does not necessarily indicate that all stream temperatures in the range of observation have increased. If the slope increases while the intercept remains stable, this indicates that all temperatures greater than where the pre- and post-harvest regression lines meet are greater after harvesting than before harvesting. Temperatures that fall below where the pre- and post-harvest lines cross will be cooler after harvesting. Therefore, if significant changes to either slope alone or both slope and intercept are confirmed, it is important to consider the range of temperatures over which changes have occurred. For instance, we detect significant decreases in slopes related to mean and minimum temperatures in all streams. However, depending upon the range of temperatures in question, this slope change may signify post-harvest temperatures which are either higher or lower than pre-harvest temperatures. Particularly in combination with the significantly decreased intercepts we observe, the observed slope decreases indicate cooler minimum temperatures on days when reference stream temperatures are high and less obvious change on cooler days.

4.5. The role of logging slash

Shade provided by logging slash may have influenced outcomes of this study. After harvesting, streams were partially covered by a layer of organic material left when the merchantable timber was removed. The logging slash attenuated solar radiation and likely moderated increases in stream temperature. However, the presence of logging slash in and around headwater streams is not considered a positive or even benign effect. In addition to the fact that the logging slash only excludes solar radiation temporarily, there are potential ecosystem-level problems that may arise from the input of such large quantities of organic matter into the stream system. As slash decomposes, the biological oxygen demand within the stream increases and dissolved oxygen (DO) concentrations are depleted (Berry, 1975; Moring and Lantz, 1975; Ice, 2008). Reduced levels of dissolved oxygen in streams, in conjunction with increased stream temperatures, can affect the survival and growth of salmonids in forested headwater streams and in some cases has led to direct mortality (Hall and Lantz, 1969; Ice, 2008). Additionally, large inputs of logging slash can alter channel morphology and particle size distributions (Jackson et al., 2001) which can potentially affect habitat quality for aquatic biota. Potential slash-related impacts such as the aforementioned were not investigated in this study, thus we are unable to comment on slash-related effects beyond the temporary exclusion of solar radiation from streams, which we observed directly.

4.6. Effect of changing forest practices

By comparing results of this stream temperature study with the documented experiences in Needle Branch in the original Alsea Watershed study, we may discern consequence of changes in forest stands and logging practices that have occurred since the Alsea Watershed experiment. The forest stand harvested in the Alsea Watershed study was a fire-regenerated, 120- to 140-year old stand of Douglas-fir. The trees that were harvested were felled directly into the stream and processed in place. The logs were yarded with a highlead cable yarding system that provided, at best, one end suspension and, more likely, no suspension or ground lead. By contrast the harvested forests at Hinkle Creek were harvest-regenerated 50- to 60-year old stands of Douglas-fir. The trees were felled by hand but contemporary practices require that they be felled away from or parallel to the stream and not into it. The proportion of defect from these trees was smaller. The logging system was a skyline system that lifted felled trees, such that trees were fully suspended over the streams and lower portions of the hillslopes. Branches that fell onto the stream were suspended or supported by the large wood already in the stream. Thus, the slash deposited in a layer over the stream. Given the changes that have taken place in forest practices over the past four decades, and the potential for change in related hydrologic effects, there is a paucity of research results that describe impacts of contemporary timber harvest adjacent to small, non-fish-bearing streams. However, the stream temperature studies that are available to assess effects of modern forest practices present conclusions similar to the ones described in this paper. For instance, Jackson et al. (2001) also report similar observations regarding the presence of logging slash over the streams, with similar implications as to stream temperature effects. Janisch et al. (2012) also investigated the impact of contemporary timber harvest on the temperature of small, non-fish-bearing streams and reported effects to maximum stream temperatures that are similar to the results reported in this paper. In order to properly evaluate current policies, there is a need for further updated study of contemporary forest practices and their effects to hydrology and aquatic habitats.

5. Conclusions

Clearcut forest harvesting adjacent to four non-fish-bearing streams in southwestern Oregon triggered statistically significant changes to summer stream temperatures. Maximum daily stream
temperatures responded significantly to the harvesting treatment, yet directions of response varied from stream to stream, as maximum temperatures in three streams became slightly warmer after harvesting and moderately cooler in the fourth. Magnitudes of maximum temperature changes were not as large as expected. Anticipated increases to maximum temperatures were not observed, likely because logging slash covered the harvested streams, blocking solar radiation after the overstory canopy had been removed, and because stream baselines increased significantly after harvesting. Statistically significant changes to relationships between treatment and reference streams with respect to minimum and mean stream temperatures also resulted in decreased minimum daily stream temperatures on days when high temperatures were observed in reference streams. Results clearly indicate that decreased minimum stream temperatures are a potential consequence of timber harvest.

When results are averaged over the four individual streams, we observe that minimum temperatures decreased significantly but that changes to maximum temperatures were not significant. Much detail regarding individual catchment response and potential response mechanisms is lost in the averaging of data across several streams. A watershed-scale analysis of the cumulative stream temperature effect of four spatially-distributed harvest units indicates that there was no significant change to maximum, mean, or minimum stream temperatures at the watershed outlet.

One year after forest harvesting, we observed that logging slash provided canopy cover after forest canopies were removed, likely affecting energy balances within clearcut headwater streams. Logging slash may influence other aspects of stream ecosystems. The effect of slash loading to streams deserves further study to support informed management practices.

References


