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A catchment-scale assessment of stream temperature response to contemporary forest harvesting in the Oregon Coast Range

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ABSTRACT

Historical forest harvesting practices, where the riparian canopy was removed, generally increased energy loading to the stream and produced higher stream temperatures. As such, contemporary forest management practices require maintenance of streamside vegetation as riparian management areas, with an important function of providing shade and minimizing solar radiation loading to streams to mitigate stream water temperature changes. The Alsea Watershed Study Revisited in the Oregon Coast Range provided a unique opportunity to investigate and compare the stream temperature responses to contemporary forest harvesting practices (i.e., maintenance of riparian vegetation) with the impacts from historical (1960s) harvesting practices (i.e., no riparian vegetation). Here we present an analysis of 6 years (3 years pre-harvest and 3 years post-harvest) of summer stream temperature data from a reference (Flynn Creek) and a harvested catchment (Needle Branch). There was no evidence that the (a) 7-day moving mean of daily maximum ($T_{7DAYMAX}$) stream temperature, (b) mean daily stream temperature, or (c) diel stream temperature changed in the study stream reaches following contemporary forest harvesting practices. The only parameter of interest that changed after forest harvesting was the $T_{7DAYMAX}$ when analyses were constrained to the Oregon regulatory period of July 15 to August 15 and all sites in each catchment were grouped together—in this case stream temperature increased 0.6 ± 0.2 °C ($p = 0.002$). However, over the entire post-harvest study period, the warmest maximum daily stream temperature observed in Needle Branch was 14.7 °C—in the original Alsea Watershed Study, maximum daily stream temperatures rose to 21.7 °C (1966) and 29.4 °C (1967) in the first two post-harvest years, providing evidence that current harvesting practices have improved protection for stream water temperatures.

1. Introduction

Preventing or mitigating changes in the thermal regime following land use activities, such as forest harvesting, is a primary focus of contemporary forest watershed management (Hester and Doyle, 2011). Historical research has shown that forest harvesting, where the riparian canopy is removed, can increase energy loading to the stream and produce higher stream temperatures (Levno and Rothacher, 1967; Moore et al., 2005; Studinski et al., 2012). The original Alsea Watershed Study (AWS; 1958–1973) in the Oregon Coast Range demonstrated that clear-cut harvesting with complete removal of riparian vegetation can result in dramatic changes in mean daily, maximum daily, diurnal variation, and annual patterns in stream temperature (Brown and Krygier, 1970). Strips of vegetation left along Deer Creek in the original AWS also demonstrated the benefit of streamside trees for reducing the impacts of forest harvesting on stream temperature (Brown and Krygier, 1970; Ice et al., 2004; Ice, 2008). Results from this historical research were instrumental to the creation of the Oregon Forest Practices Act of 1971, which called for retention of streamside vegetation (18–30 m riparian management zones) in private harvest units as a best management practice for the maintenance of water quality and aquatic habitat (Ice and Stednick, 2004).

One of the most desirable functions of riparian areas is to maintain water temperatures after forest harvesting by minimizing solar radiation input to streams (Hester and Doyle, 2011). This is because stream temperature is one of the most important physical water quality parameters that can influence the structural and functional characteristics of stream and river aquatic ecosystems (Vannote et al., 1980; Poole and Berman, 2001; Clarke, 2006). Stream temperatures affect the metabolic and physical processes of aquatic organisms (Brown et al., 2004; Leach et al., 2012), the behavioral ecology of aquatic organisms (Torgersen et al., 1999;

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Wenger et al., 2011), and the rates of in-stream chemical processes (Demars et al., 2011). As such, stream temperature is a fundamental determinant of habitat for most aquatic organisms, including phytoplankton, zooplankton, macroinvertebrates, and fish (Beitinger and Fitzpatrick, 1979; Vannote and Sweeney, 1980). Cold-water fish species, such as Pacific salmonids, are adapted to the spatial and temporal temperature patterns experienced in their native ranges and are particularly sensitive to fluctuations in water temperature through all stages of their life history (Dunham et al., 2003; McCullough et al., 2009). Rapid and extreme alterations in water temperature regimes can result in dispersal, increased vulnerability to predation, acute thermal shock, or mortality (Beschta et al., 1987; Quigley and Hinch, 2006).

Recent experiments have shown that riparian management areas (RMAs) consisting of mature timber that preserves some percentage of pre-harvest canopy closure to maintain stream shade may be effective at minimizing the effects of forest harvesting on stream temperature (Macdonald et al., 2003; Gomi et al., 2006; Groom et al., 2011; Cole and Newton, 2013). In theory, maintenance of shade should be an effective strategy to mitigate stream temperature changes following forest harvesting as direct solar radiation and atmospheric conditions are often the primary driver for summer stream temperatures (Sinokrot and Stefan, 1993; Johnson, 2004). There is still, however, considerable debate and uncertainty about the effectiveness of contemporary practices and the design of buffers (DeWalle, 2010; Newton and Ice, 2016). In part, this is due to the lack of scientific underpinnings for riparian guidelines in many regions (Blinn and Kilgore, 2001). While many jurisdictions vary widely in their riparian buffer guidelines due to differences in climate, economic, and social factors (Lee et al., 2004), many have simply adopted regulations from other forested landscapes without any empirical research to test their local efficacy (Richardson et al., 2012). Since much of the understanding on the effectiveness of riparian forest buffers originates from studies examining historical (middle 20th century) forest harvesting practices, these results do not accurately reflect contemporary practices (Brown and Krygier, 1971; Holtby, 1988; Johnson and Jones, 2000). As such, further analysis is needed to assess the effectiveness of contemporary forest management practices at mitigating the impacts on stream temperature.

The Alsea Watershed Study Revisited provided a unique opportunity to investigate and compare the stream temperature responses to contemporary forest harvesting practices (e.g., retention of riparian vegetation for provision of shade) with the impacts from historical (1960s) harvesting practices (e.g., no riparian vegetation retained). The AWS was reactivated in 1990 to assess long-term responses of the catchments to commercial forest harvesting (Stednick, 2008). As an extension of the reactivation of the site, a study of current forest harvest practices on private timberlands began in 2006. The upper portion of the Needle Branch catchment was harvested in 2009 according to the Oregon Forest Practices Act, including RMAs. Here, we present analysis of 6 years (3 years pre-harvest and 3 years post-harvest) of summer stream temperature data from the reference (Flynn Creek) and harvested catchments (Needle Branch) to address three research questions:

(1) Did the 7-day moving mean of daily maximum ($T_{7DAYMAX}$) stream temperature change following contemporary forest harvesting?
(2) Did mean daily stream temperature (T_{DAY}) change following contemporary forest harvesting?
(3) Did the diel stream temperature (T_{DIEL}) change following contemporary forest harvesting?

2. Methods

2.1. Site description

The Alsea Paired Watershed Study Revisited (44.5°N, 123.9°W) was constructed as a paired-watershed study (Fig. 1), with a reference catchment (Flynn Creek, 219 ha) and a nearby treatment catchment (Needle Branch, 94 ha), which was harvested in 2009 with RMAs according to the Oregon Forest Practices Act (OFPA) (Table 1). The study area is located in the Siuslaw National Forest in the Oregon Coast Range, which is highly-dissected and mountainous and characterized by short, steep, soil-mantled hillslopes. Both catchments are underlain by Eocene Tyee Formation sandstone and siltstone. Mean elevation in Flynn Creek is 280 m and in Needle Branch is 220 m. The mean gradient of Flynn Creek is 27.9°, while Needle Branch is considerably steeper at 37.0°. Drainage density in Flynn Creek is 0.47 km km^{-2}, while in Needle Branch it is 1.01 km km^{-2}. In Flynn Creek, the mean wetted width was 1.34 m ± 0.11 SD with mean maximum pool depths of 0.25 m ± 0.03 SD and mean maximum riffle depths of 0.09 m ± 0.02 SD. In Needle Branch, the mean wetted width was 1.11 m ± 0.15 SD with mean maximum pool depths of 0.25 m ± 0.04 SD and mean maximum riffle depths of 0.07 m ± 0.02 SD. Stream wetted widths and depths are representative of typical summer baseflow conditions, during the peak summer temperature period, in the Oregon Coast Range. The channel substrate in Flynn Creek primarily consisted of gravels (42.6% ± 0.08 SD) and fines (<1 mm; 19.1% ± 0.04 SD) with lesser amounts of cobbles, boulders, and bedrock. Similarly, Needle Branch is also primarily gravels (45.0% ± 0.10 SD) and fines (<1 mm; 28.9% ± 0.08 SD) with occasional cobbles, boulders, and bedrock. Catchments are principally south facing, with mean slope aspects of 188° in Flynn Creek and 189° in Needle Branch.

Forest vegetation in Needle Branch was primarily even-age (44-yr-old), dominated by Douglas-fir (*Pseudotsuga menziesii*) with patches of red alder (*Alnus rubra*) along the riparian corridors. Forest vegetation in Flynn Creek is ~155-yr-old Douglas-fir with stands of red alder dominating the riparian corridor. Study catchments support fish communities of coastal cutthroat trout (*Oncorhynchus clarkii clarkii*), coho salmon (*O. kisutch*), reticulate sculpin (*Cottus perplexus*), western brook lamprey (*Lampetra richardsoni*), and Pacific lamprey (*L. tridentata*).

Flynn Creek is principally undisturbed by human activities (during the 1960s study as well as today) and was designated as a Research Natural Area in 1975 by the USDA Forest Service. The upper sub-catchment (37.2 ha) of Needle Branch was clearcut harvested from mid-June to mid-August 2009 using contemporary harvesting practices, including both ground-based and line-based equipment. All trees in the cutover area were removed, including along 3 small, non-fish-bearing tributaries that join to form mainstem Needle Branch just above a waterfall that forms the upstream limit of fish distribution. On the fish-bearing portion of the stream, a ~15 m riparian management area (RMA) was retained on each side of Needle Branch in accordance with the Oregon Forest Practices Act and Rules (ODF, 1994). This resulted in a minimum of ~3.7 m^2 conifer basal area retained for every ~300 m of stream length. In addition, ~4–5 wildlife leave trees per hectare were retained within the RMA, as recommended by the Oregon Forest Practices Act (Adams and Storm, 2011). Mean canopy closure, as measured with a densiometer, along the stream channel in the harvested portion of Needle Branch was reduced from ~96% in the pre-harvest period to ~89% in the post-harvest period. Comparatively, mean canopy closure along the stream channel in Flynn Creek was ~92% in the pre-harvest period and ~91% in the post-harvest period.

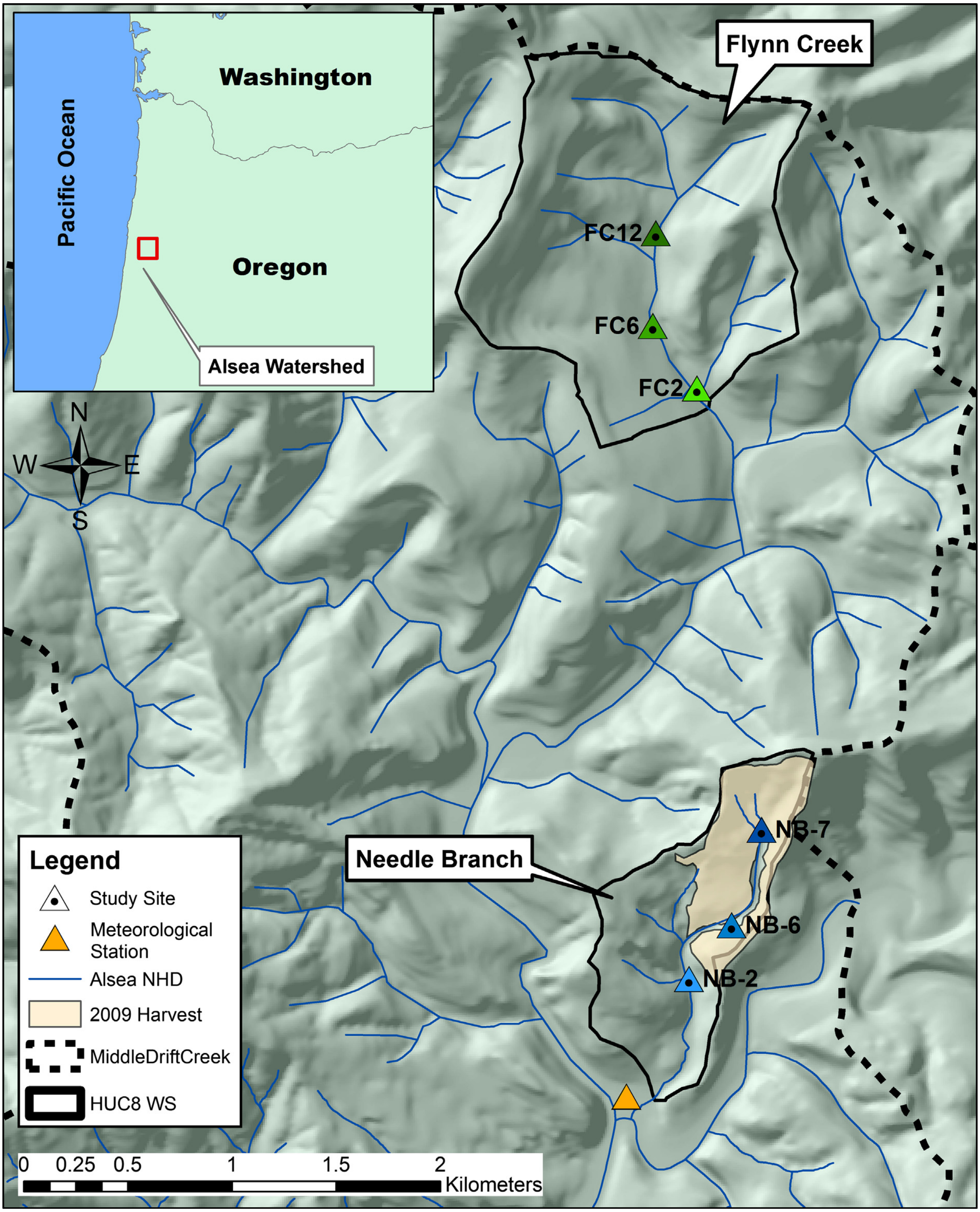

Fig. 1. Map of the Alsea Watershed Study catchments (Flynn Creek and Needle Branch), including locations of the stream temperature measurement sites and the harvested area.

2.2. Stream temperature measurements

Stream temperature (T_s) thermistors in Needle Branch were located within the harvested portion (within a stream reach with riparian vegetation retained) of the upper catchment (NB7), mid-catchment above the outlet of the harvested portion of the catchment (NB6), and below the harvest, within the unharvested portion of the catchment (NB2) (Fig. 1). In Flynn Creek, T_s thermistors were also located in the upper (FC12), mid (FC6), and lower (FC2) reaches of the stream (Fig. 1). Sites were paired beginning with the uppermost thermistors (i.e., FC12 and NB7) – additional thermistor pairs across the control (Flynn Creek) and harvested (Needle Branch) catchments were selected at a thalweg distance between thermistor deployments on each stream of approximately

Table 1
Sub-catchment areas, upstream harvested area, and percent of sub-catchment harvested above each of the thermistor sites.

Catchment	Site	Sub-catchment area (km^2)	Harvest area upstream of site (km^2)	% of sub-catchment harvested
Flynn Creek	FC12	0.80	–	–
	FC6	1.53	–	–
	FC2	2.10	–	–
Needle Branch	NB7	0.13	0.13	100.0
	NB6	0.28	0.25	89.3
	NB2	0.62	0.37	59.6

400–500 m (i.e., FC6 and NB6; FC2 and NB2). Measurements were taken at 30-min intervals using Onset TidbiT water temperature data loggers (UTBI-001, Onset Corporation, Bourne, MA; accuracy ±0.21 °C). Prior to deployment each season, data loggers were calibrated against each other and tested for responsiveness in a controlled environment by placing in a slurry of water and ice for 30 min at a high sampling frequency. Loggers that were non-responsive or recorded temperatures outside of the specifications (i.e., ±0.21 °C) were replaced with new loggers. Loggers were deployed from mid-June or early July to early September to measure during the warmest time of the year through both the pre-harvest (2006–2008; Fig. 2) and post-harvest (2010–2012; Fig. 3) periods. Temperature sensors were shielded from direct solar radiation by placing in rock cairns with the ends open parallel to stream flow to ensure good mixing.

2.3. Statistical analyses

Using a paired before-after control-impact (BACIP) design, paired sites between the reference (Flynn Creek) and harvested (Needle Branch) catchments were analyzed to detect changes in the 7-day moving mean of the daily maximum stream temperature ($T_{7DAYMAX}$), mean daily stream temperature (T_{DAY}), and diel stream temperature fluctuation (T_{DIEL}) due to time (pre- vs. post-harvest period), treatment (control catchment and harvested catchment), and the interaction of treatment and time (BACI effect). All data were analyzed using the restricted maximum likelihood estimation (REML) in a random-intercept, linear mixed-effects model with the *nlme* package (Pinheiro et al., 2016) in R (R Core Team, 2014). The model form was:

$$T_S = period + location + BACI + (\sim 1|\text{Water Year/Site}) + \varepsilon_t \qquad (1)$$

where ε_t represents the ARMA-corrected error term selected using *corARMA*(). To account for the repeated sampling of fixed spatial locations (pseudoreplication) and autocorrelation (non-independence) of stream temperature observations, autoregressive-moving average (ARMA) terms were included in the model. ARMA terms (p,q) were allowed to vary from $0 \leqslant (p,q) \leqslant 4$, such that Akaike Information Criterion (AIC) was minimized. Residual plots, autocorrelation function plots, and partial autocorrelation plots were consulted to determine model stationarity and ARMA coefficient appropriateness. The resulting ARMA structures for all metrics were $(p,q) = (1,1)$. The fixed effects in the model were *period* (temporal stream temperature differences from the pre-harvest period to the post-harvest period in the reference catchment [Flynn Creek]), *location* (difference in the mean of the analyzed temperature metric during the pre-harvest period between Flynn Creek and Needle Branch), and *BACI* (difference in the mean of the analyzed temperature metric between the pre-harvest period in Flynn Creek and the post-harvest period in Needle Branch; interaction between period and location).

While the intent was to test the fixed effects, the model also needed to account for the random effects (i.e., temporal and spatial

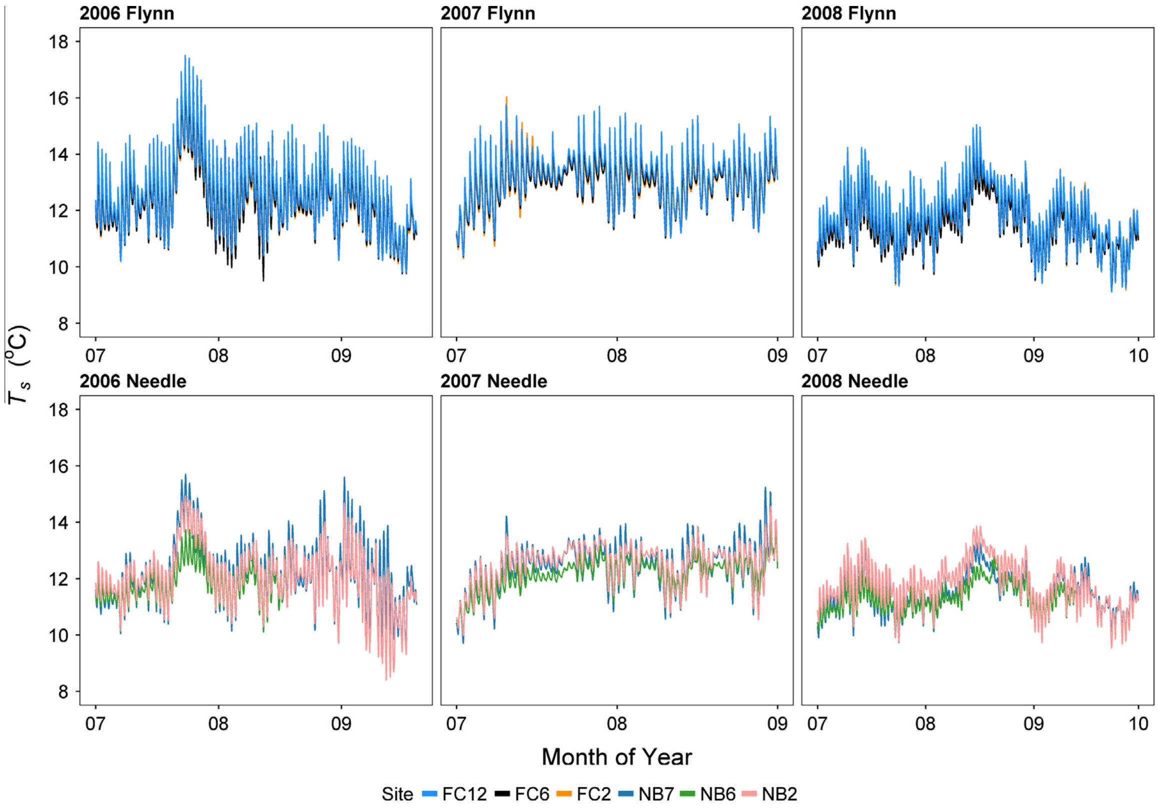

Fig. 2. Pre-harvest (2006–2008) July to September stream temperature (T_S) at longitudinal sites on Flynn Creek (FC12, FC6, FC2; reference) and Needle Branch (NB7, NB6, NB2; harvested) at 30 min intervals.

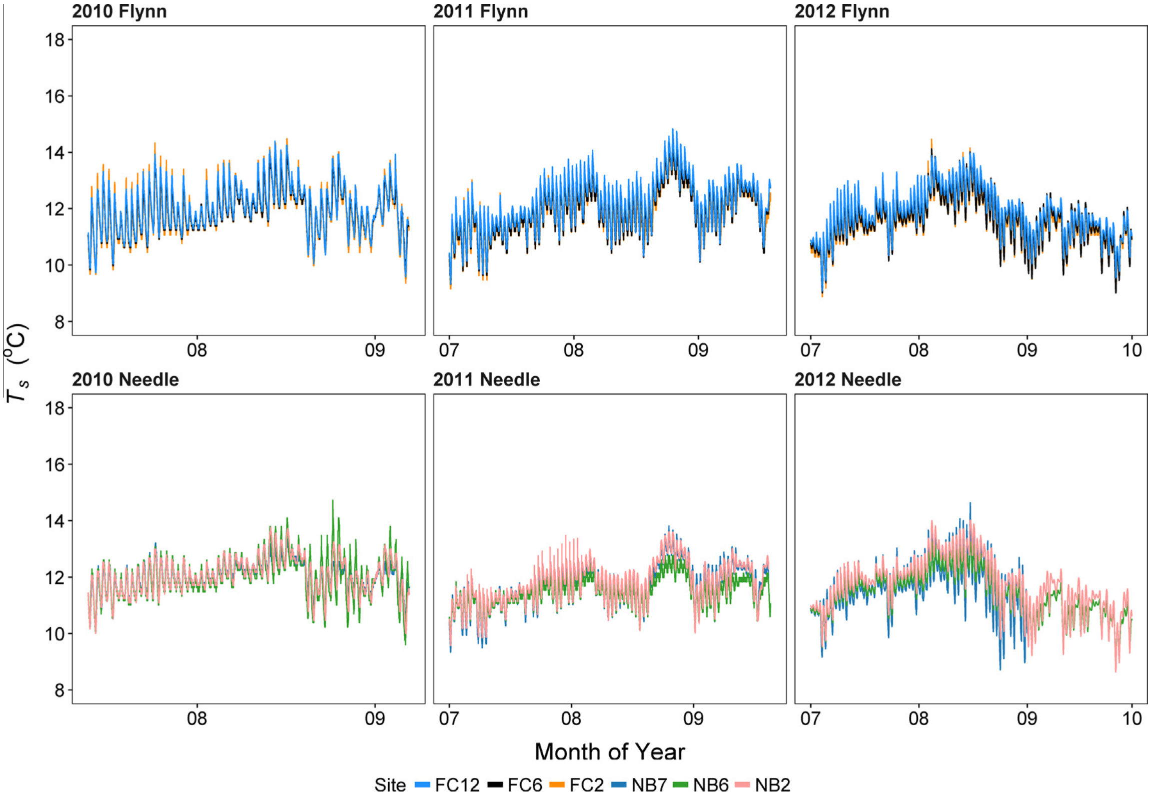

Fig. 3. Post-harvest (2010–2012) July to September stream temperature (T_S) at longitudinal sites on Flynn Creek (FC12, FC6, FC2; reference) and Needle Branch (NB7, NB6, NB2; harvested) at 30 min intervals.

variability). By using the likelihood ratio test to compare models using different random effects, the nesting of site within year provided the best model fit as opposed to either site or year as independent random effects. The inclusion of this random effect accounted for year-to-year variability in the data. To test the size of fixed effects, the Wald test was performed on the results of the model. The results of the model provide coefficient estimates, which indicate the differences in means of the analyzed metric due to each fixed factor individually as well as the interaction of the two (the BACI effect). While the model coefficients indicate differences in means between subgroups of data, use of the Wald test provides a way to compare the effect sizes of these fixed factors to determine their impact on the data. Thus, results of the different models are reported as factor coefficient ± SE, p-value of F-statistic. Through these procedures, assessment of the strength of evidence regarding the effects on stream temperature due to the period of observation (pre-harvest or post-harvest), the location (control catchment or treatment catchment), or the forest harvest itself (post-harvest, treatment basin) could be completed while accounting for both annual and site variability.

Table 2
Mean monthly and mean monthly maximum air temperatures (°C, July to September) from 2006 to 2012 at the Alsea Watershed Study.

Year	Jul	Aug	Sep
		Mean monthly	
2006	15.6	14.0	13.8
2007	15.4	15.0	13.2
2008	14.8	14.7	12.3
2009	15.9	14.9	13.5
2010	13.8	14.2	13.5
2011	13.5	–	14.3
2012	14.4	14.7	12.4
		Mean monthly maximum	
2006	23.7	21.9	21.6
2007	22.3	22.0	20.2
2008	22.6	21.6	21.6
2009	23.5	22.1	22.0
2010	20.8	21.3	21.1
2011	20.8	–	23.7
2012	20.0	22.9	22.2

3. Results

3.1. Meteorology and discharge

During the pre-harvest period (2006–2008), the July to September mean daily air temperature (T_a) from a centrally located meteorological station was 14.0 °C and mean daily maximum T_a was 21.9 °C (Table 2). In the post-harvest period (2010–2012), the July to September mean daily T_a was 14.0 °C and mean daily maximum T_a was 21.4 °C (Table 2).

Mean annual precipitation in the pre-harvest years was 2486 mm, with ~75.1 mm (range: 61.5–96.0 mm) falling during the stream temperature measurement period of July to September. Similarly, in the post-harvest years mean annual precipitation was 2502 mm with an average of 61.7 mm (range: 21.1–106.9 mm) falling from July to September. As such, the majority of precipitation (~85%) falls as rain from October through April during long-duration, low-to-moderate intensity frontal storms.

Pre-harvest mean discharge in Needle Branch during the stream temperature measurement period of July to September was 1.6 L s^{-1} ± 0.1 SE. During the post-harvest period mean discharge (July to September) in Needle Branch was 3.8 L s^{-1} ± 0.1 SE. While baseflow was elevated in the post-harvest years compared to the pre-harvest years, high flows remained relatively stable across the period of study (Fig. 4).

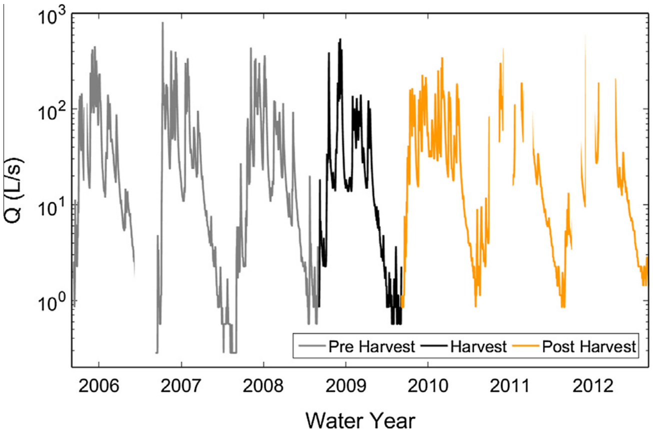

Fig. 4. Discharge ($L\,s^{-1}$) time-series from Needle Branch from 2006 to 2012.

Table 3
Coefficients and effect sizes from the linear mixed-effects model for $T_{7DAYMAX}$ at each of the longitudinal site-pairs across the harvested (Needle Branch, NB) and reference (Flynn Creek, FC) catchments.

Pair	Effect	Model coefficients		Effect size	
		Intercept	S.E.	*F*	*p*-value
NB7-FC12 (upper catchment)	Period	−0.7	0.5	2.8	0.17
	Location	−0.3	0.5	0.4	0.57
	BACI	0.2	0.7	0.1	0.75
NB6-FC6 (mid-catchment)	Period	−0.7	0.5	2.4	0.20
	Location	−0.7	0.5	2.2	0.21
	BACI	0.4	0.7	0.4	0.58
NB2-FC2 (lower catchment)	Period	−1.0	0.5	4.4	0.10
	Location	−0.9	0.5	3.5	0.14
	BACI	0.6	0.7	0.7	0.46

3.2. Stream temperature

During the pre-harvest period (2006–2008), the 7-day moving mean of the daily maximum stream temperature ($T_{7DAYMAX}$) from July to September was ~0.4–1.0 °C cooler in Needle Branch sites (harvested) compared to paired sites in Flynn Creek (reference) (Fig. 5). Statistical analysis of $T_{7DAYMAX}$ in the pre-harvest period provided evidence that the Needle Branch sites were innately cooler compared to paired Flynn Creek sites in the mid-catchment (NB6 v. FC6) and lower catchment (NB2 v. FC2), while there was no evidence of a difference in $T_{7DAYMAX}$ between the upper catchment sites (NB7 v. FC12) (Table 3, location effect). Across all sites, statistical analysis of the $T_{7DAYMAX}$ also indicated that Needle Branch was generally cooler than Flynn Creek in the pre-harvest period (-0.7 ± 0.2 °C, $p = 0.01$).

From the pre-harvest to the post-harvest period the $T_{7DAYMAX}$ cooled in all stream reaches in Flynn Creek (range: 0.6–1.0 °C) and in Needle Branch (range: 0.1–0.3 °C) (Fig. 5). However, there was no evidence that the cooling in the reference catchment was statistically different across periods at each of the individual sites (Table 3, period effect) or across all of the Flynn Creek sites combined (-0.8 ± 0.3 °C, $p = 0.06$). Comparisons of descriptive statistics of $T_{7DAYMAX}$ across the paired sites indicated that site pairs became more similar from the pre-harvest to the post-harvest period, but the $T_{7DAYMAX}$ remained ~0.1–0.5 °C cooler in Needle Branch sites compared to paired sites in Flynn Creek (Fig. 5). Despite more similar $T_{7DAYMAX}$ in the post-harvest period, model analysis across all sites also indicated that Needle Branch remained cooler than Flynn Creek (-0.3 ± 0.2 °C, $F = 7.0$, $p = 0.01$).

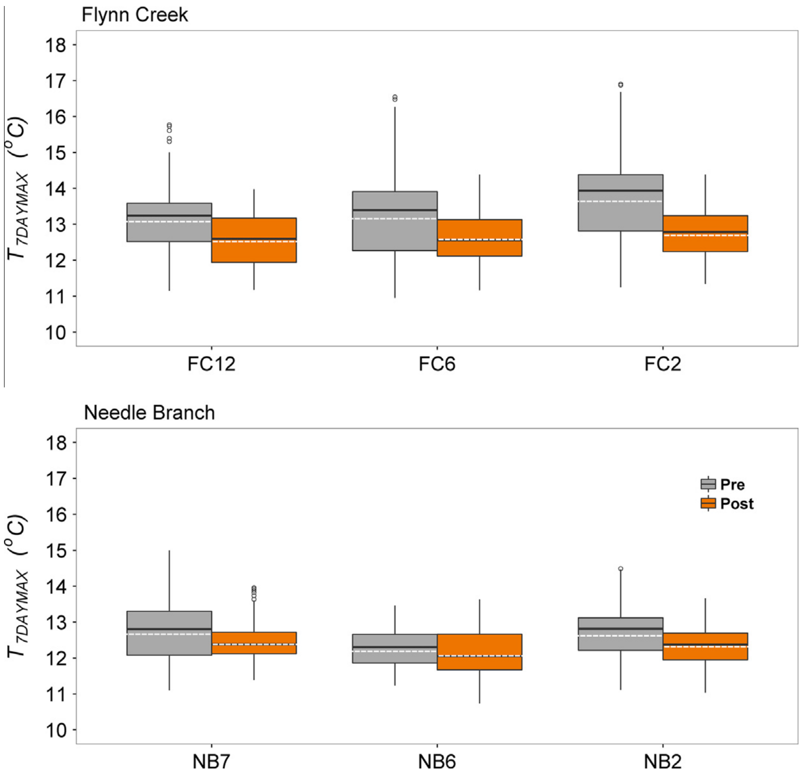

Fig. 5. 7-Day rolling maximum of stream temperature ($T_{7DAYMAX}$) during the pre-harvest (2006–2008; gray boxplots) and post-harvest (2010–2012; orange boxplots) years across each site in Flynn Creek (FC, reference) and Needle Branch (NB, harvested). The solid line represents the standard boxplot median, while the dashed white line represents the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To isolate potential harvesting effects on $T_{7DAYMAX}$, the site pairs were correlated against each other prior to investigating the BACI effect in the model. The $T_{7DAYMAX}$ was weakly to moderately correlated between the paired sites in the reference and harvested catchments both before and after timber harvest, generally increasing in the downstream sites (Fig. 6). After accounting for the intrinsic annual and site variability, individual pairwise comparisons between the upper, mid, and lower catchment pairs did not indicate increases to $T_{7DAYMAX}$ (July to September) in Needle Branch following harvesting (Table 3, BACI effect). Similarly, there was no evidence that the $T_{7DAYMAX}$ changed following harvesting activity when comparing across all catchment sites combined (0.4 ± 0.4 °C, $p = 0.27$).

Constraining the time period of analyses to the current Oregon regulatory period of July 15 to August 15, the $T_{7DAYMAX}$ was ~0.6–1.3 °C cooler in Needle Branch sites (harvested) compared to paired sites in Flynn Creek (reference) during the pre-harvest period (−1.0 ± 0.1 °C, $p < 0.001$). Despite the $T_{7DAYMAX}$ in the Needle Branch sites remaining ~0.3–0.5 °C cooler than in Flynn Creek during the post-harvest period (regulatory time frame only) (−0.4 ± 0.1 °C, $p = 0.004$), the difference between the catchments diminished considerably. Thus, when comparing across all sites combined within each catchment, there is evidence that the $T_{7DAYMAX}$ in the July 15 to August 15 period changed following the harvesting activity in Needle Branch (0.6 ± 0.2 °C, $p = 0.002$). However, after accounting for the intrinsic annual and site variability, individual pairwise comparisons between the upper (0.3 ± 0.3 °C, $p = 0.31$), mid- (0.7 ± 0.4 °C, $p = 0.17$), and lower catchment pairs (0.8 ± 0.3 °C, $p = 0.06$) did not indicate increases in the $T_{7DAYMAX}$ in Needle Branch after harvesting.

There was weak or no evidence that the pre-harvest (July to September) mean daily stream temperature (T_{DAY}) was cooler in any of the Needle Branch sites compared to paired sites in Flynn Creek (Table 4, location effect). Combining all of the sites together within each catchment, indicated that T_{DAY} was ~0.2–0.4 °C cooler in the Needle Branch sites compared to paired sites in Flynn Creek (Fig. 7). As such, the T_{DAY} was considered to be statistically dissimilar between Needle Branch and Flynn Creek in the pre-harvest period (−0.3 ± 0.1 °C, $p = 0.01$).

There was no evidence that the post-harvest (2010–2012) T_{DAY} at each of the individual sites in Flynn Creek was different from the pre-harvest T_{DAY} (Table 4, period effect). Similarly, there was no evidence that T_{DAY} had changed significantly from the pre-harvest to the post-harvest period across all of the Flynn Creek sites combined (−0.5 ± 0.3 °C, $p = 0.22$). In comparisons with paired sites in Flynn Creek, the descriptive statistics indicated that the T_{DAY} remained, on average, ~0.2 °C cooler in the two downstream Needle Branch sites (NB2 and NB6) during the post-harvest period. However, the T_{DAY} at the upstream site in Needle Branch (NB7) compared to its paired site in Flynn Creek (FC12)

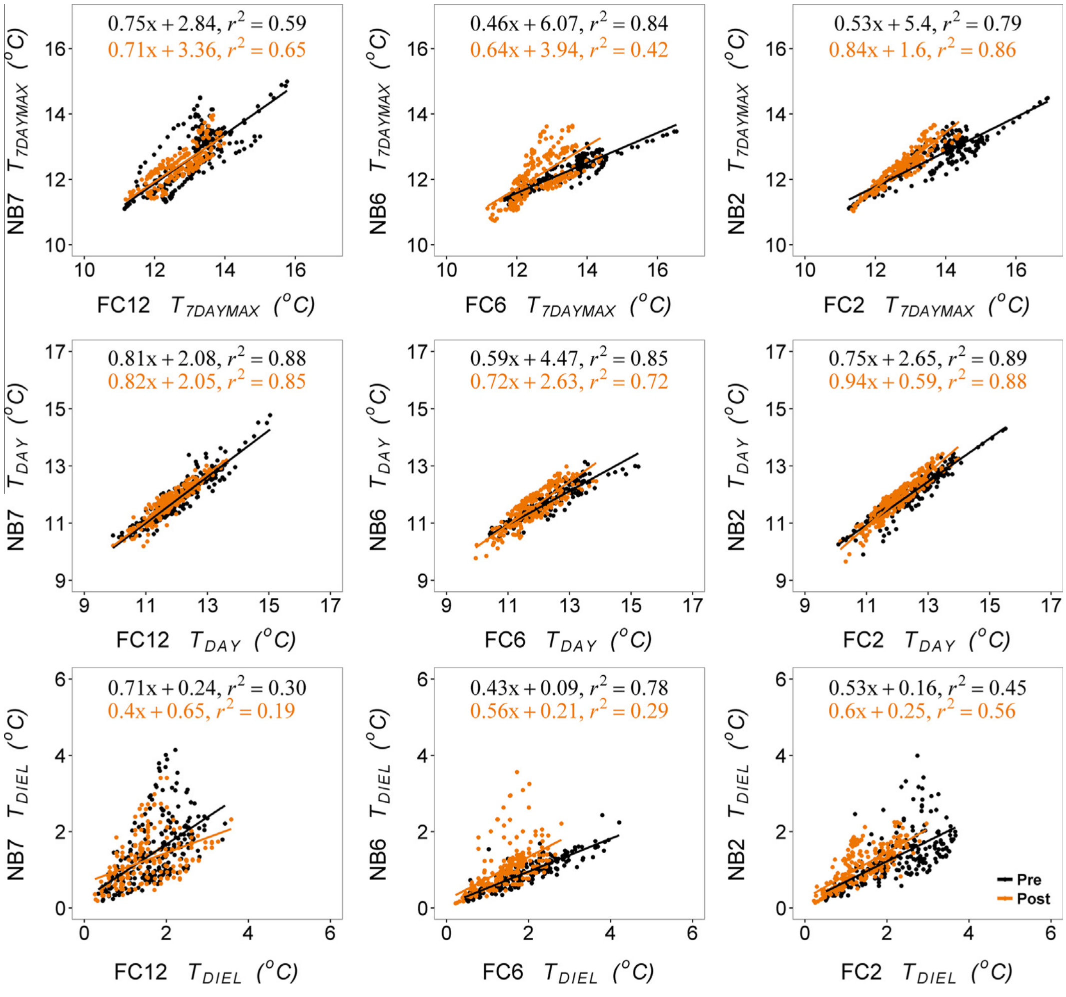

Fig. 6. Pre-harvest (2006–2008; black) and post-harvest (2010–2012; orange) July to September 7-day rolling maximum of stream temperature ($T_{7DAYMAX}$), mean daily stream temperature (T_{DAY}), and mean diel stream temperature variation (T_{DIEL}) relationships between Flynn Creek (FC, reference) and Needle Branch Creek (NB, harvested). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Coefficients and effect sizes from the linear mixed-effects model for T_{DAY} at each of the longitudinal site-pairs across the harvested (Needle Branch, NB) and reference (Flynn Creek, FC) catchments.

Pair	Effect	Model coefficients		Effect size	
		Intercept	S.E.	F	p-value
NB7-FC12 (upper catchment)	Period	−0.5	0.4	1.5	0.29
	Location	−0.2	0.2	0.6	0.48
	BACI	0.2	0.3	0.7	0.45
NB6-FC6 (mid-catchment)	Period	−0.4	0.4	1.0	0.37
	Location	−0.4	0.2	4.4	0.10
	BACI	0.2	0.3	0.3	0.61
NB2-FC2 (lower catchment)	Period	−0.6	0.3	1.9	0.24
	Location	−0.4	0.2	2.9	0.16
	BACI	0.2	0.3	0.5	0.52

was approximately the same temperature (Fig. 7). Because these differences were small, comparisons across all sites combined within each catchment indicated that the T_{DAY} in Needle Branch was generally similar to Flynn Creek in the post-harvest period (-0.1 ± 0.1 °C, $p = 0.28$). This observation represents a slight deviation from pre-harvest conditions, where Needle Branch was statistically cooler than Flynn Creek.

To isolate potential harvesting effects on T_{DAY}, the site pairs were correlated against each other prior to investigating the BACI effect in the model. The T_{DAY} had moderate to strong positive correlation between the paired sites both before and after timber harvest (Fig. 6). After accounting for the inherent site and annual variability, model results indicated that there was no evidence of increased T_{DAY} at Needle Branch when compared with paired sites in Flynn Creek following harvesting (Table 4, BACI effect). Analysis of all catchment sites combined within each catchment also indicated that there was no evidence that T_{DAY} changed in Needle Branch after forest harvesting (0.2 ± 0.2 °C, $p = 0.25$).

The mean diel stream temperature fluctuation (T_{DIEL}) was generally less variable at all sites in Needle Branch compared to Flynn Creek during the pre-harvest period, (~0.2–0.9 °C; Fig. 8). Statistical analysis of T_{DIEL} in the pre-harvest period provided evidence that the Needle Branch sites were innately less variable compared to paired Flynn Creek sites in the mid-catchment (NB6 v. FC6) and lower catchment (NB2 v. FC2), while there was no evidence of a difference in T_{DIEL} between the upper catchment sites (NB7 v. FC12) (Table 5, location effect). Across all sites, statistical analysis of the T_{DIEL} also indicated that Needle Branch was generally less variable than Flynn Creek in the pre-harvest period (-0.6 ± 0.1 °C, p =< 0.001).

From the pre-harvest to the post-harvest period the mean T_{DIEL} decreased in all stream reaches in Flynn Creek (range: 0.2–0.7 °C). However, the decrease in T_{DIEL} in the Flynn Creek was not statistically different between the pre-harvest and post-harvest period at each of the individual sites (Table 5, period effect) or across all of the Flynn Creek sites combined (-0.4 ± 0.2 °C, $p = 0.19$). In Needle Branch, the T_{DIEL} decreased in the uppermost (NB7) and lower (NB2) stream reaches (range: 0.1–0.2 °C), but increased in the middle stream reach at the outlet of the cutblock (NB6; 0.1 °C) (Fig. 8). Comparisons of descriptive statistics of T_{DIEL} across the paired sites indicated that sites became more similar from the pre-harvest to the post-harvest period; but, the T_{DIEL} variability remained ~0.2–0.5 °C lower in Needle Branch sites compared to paired sites in Flynn Creek (Fig. 8). Despite more similar T_{DIEL} variability in the post-harvest period, model analysis across all sites also indicated that Needle Branch still had less day-to-day variability in stream temperatures compared to Flynn Creek (-0.3 ± 0.1 °C, $p = 0.02$).

To isolate potential harvesting effects on T_{DIEL} the site pairs were correlated against each other prior to investigating the BACI

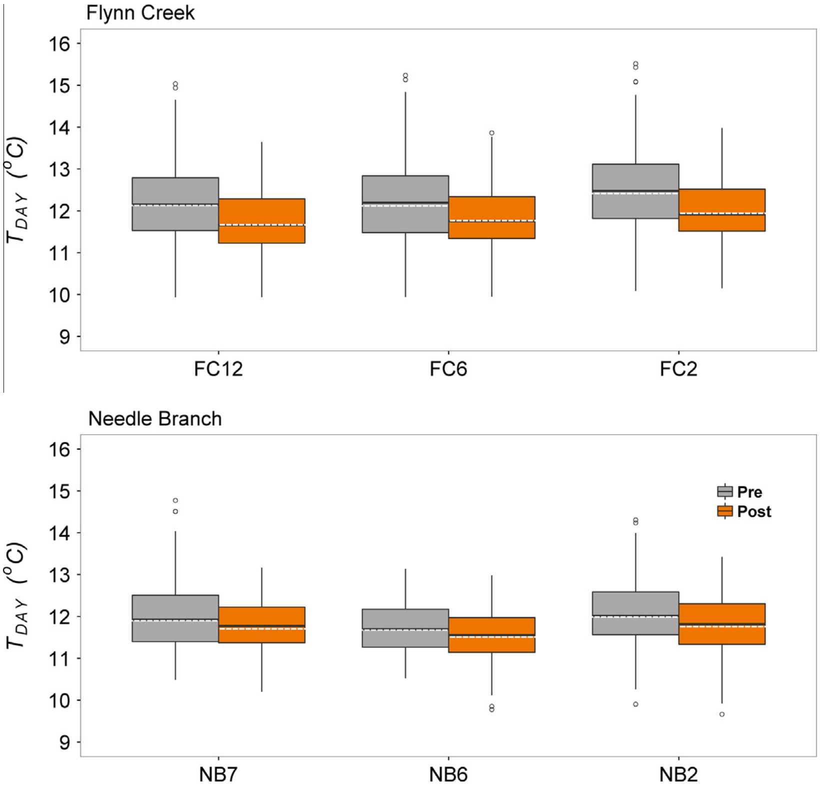

Fig. 7. Mean daily stream temperature (T_{DAY}) during the pre-harvest (2006–2008; gray boxplots) and post-harvest (2010–2012; orange boxplots) years across all sites in Flynn Creek (FC, reference) and Needle Branch (NB, harvested). The solid line represents the standard boxplot median, while the dashed white line represents the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

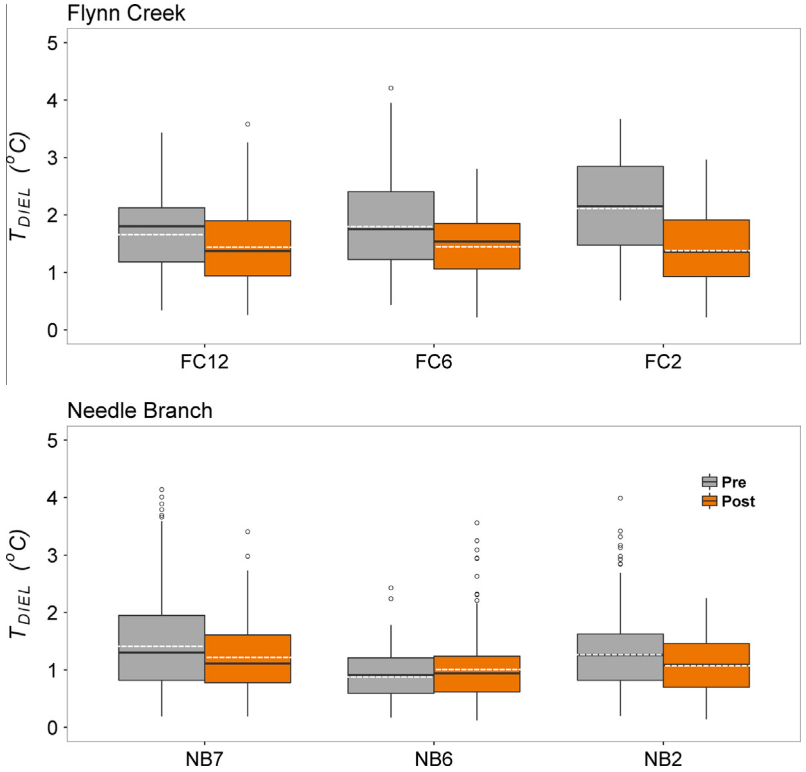

Fig. 8. Diel stream temperature (T_{DIEL}) during the pre-harvest (2006–2008; gray boxplots) and post-harvest (2010–2012; orange boxplots) years across all sites in Flynn Creek (FC, reference) and Needle Branch (NB, harvested). The solid line represents the standard boxplot median, while the dashed white line represents the mean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 5
Coefficients and effect sizes from the linear mixed-effects model for T_{DIEL} at each of the longitudinal site-pairs across the harvested (Needle Branch, NB) and reference (Flynn Creek, FC) catchments.

Pair	Effect	Model coefficients		Effect size	
		Intercept	S.E.	*F*	*p*-value
NB7-FC12 (upper catchment)	Period	−0.1	0.3	0.5	0.53
	Location	−0.2	0.3	1.1	0.36
	BACI	−0.1	0.5	0.0	0.89
NB6-FC6 (mid-catchment)	Period	−0.3	0.3	0.1	0.74
	Location	−0.9	0.2	17.4	0.01
	BACI	0.5	0.3	2.6	0.18
NB2-FC2 (lower catchment)	Period	−0.7	0.3	3.3	0.14
	Location	−0.8	0.1	31.9	0.005
	BACI	0.5	0.2	6.3	0.07

effect in the model. The T_{DIEL} was weakly to moderately correlated between the paired sites in the reference and harvested catchments both before and after timber harvest, generally increasing in the downstream sites (Fig. 6). Again, after accounting for the inherent site and annual variability, there was no evidence that T_{DIEL} changed following forest harvesting at Needle Branch when compared with paired sites in Flynn Creek (Table 5, BACI effect). Analysis of all catchment sites combined also indicated that there was no evidence that T_{DIEL} changed in Needle Branch after forest harvesting (0.3 ± 0.2 °C, $p = 0.10$).

4. Discussion

Key physical water quality parameters, the 7-day moving mean of the daily maximum stream temperature ($T_{7DAYMAX}$; Fig. 5) and mean daily stream temperature (T_{DAY}; Fig. 7), did not change following forest harvesting of a forested headwater catchment in the Oregon Coast Range using contemporary forest management practices (i.e., retention of riparian vegetation for provision of shade). The $T_{7DAYMAX}$ and T_{DAY} in the harvested stream reaches (NB7 and NB6) and downstream reach (NB2) of Needle Branch remained colder than paired reference sites in Flynn Creek both before and after forest harvesting. While the difference between Needle Branch sites and Flynn Creek sites decreased in the post-harvest period, perhaps indicating a small post-harvest warming effect in the harvested catchment, statistically there was no evidence that this shift was beyond the observed pre-harvest range. Evidence of a harvesting effect on $T_{7DAYMAX}$ was only apparent when analyses were constrained to the regulatory period of July 15 to August 15 and all sites in each catchment were grouped together; however, there was no evidence of this effect when making direct comparisons of paired sites across the harvested and unharvested catchments. Moreover, the regulatory standards for the $T_{7DAYMAX}$ in the state of Oregon are 16 °C for core cold-water fish rearing habitat, 18 °C for non-core juvenile rearing and migration, and 20 °C for migration of salmon and trout – these were never exceeded in Needle Branch. Conversely, the standard for core cold water habitat use of 16 °C was exceeded in Flynn Creek during the warmer pre-harvest period. It was exceeded ~6% of the time in FC12 (max: 16.5 °C) and ~5% of the time in both FC6 (max: 17.1 °C) and FC2 (max: 17.5 °C).

However, it is difficult to broadly interpret our results regarding RMA effectiveness beyond Oregon Coast Range catchments with similar geology and physiography, as stream temperatures can vary spatially and mixed warming and cooling patterns have been observed following harvesting, even when streams are well shaded (Dent et al., 2008). This is related to factors such as variability in climate, harvesting strategy, riparian buffer retention, and local stream factors (Cole and Newton, 2013). Thus, the effects of the harvesting on $T_{7DAYMAX}$ and T_{DAY} in this study may have been muted due to several factors, including RMA effectiveness at mitigating increased direct solar radiation loading to the stream surface (Wilkerson et al., 2006; Janisch et al., 2012). Streams in this study were oriented north-south, meaning that they would be well shaded from late morning to early afternoon by the riparian canopy, which would maximize RMA effectiveness (Gomi et al., 2006) – it is uncertain if RMAs would perform as effectively in this region on streams with different aspects. Secondly, both the catchment and channel slopes were steep, which is known to result in lower rates of warming of stream water (Kasahara and Wondzell, 2003; Tague et al., 2007). The mean catchment gradient in Needle Branch was ~10.9° steeper than the reference catchment – greater hydraulic gradient, as observed in the harvested catchment, is known to increase stream water velocities and hyporheic exchange (Harvey and Bencala, 1993; Hill et al., 1998). This could have contributed to the cooler $T_{7DAYMAX}$ and T_{DAY} in the harvested catchment throughout this study, but was less important in the original Alsea study (1960s) due to the lack of riparian vegetation and shade. Finally, substantial groundwater contributions and hyporheic exchange can buffer stream temperature patterns by decreasing a stream's sensitivity to energy inputs (Moore et al., 2005; Moore and Wondzell, 2005) – summer baseflow in the harvested catchment was ~2.4 times greater in the post-harvest period compared to the pre-harvest period despite similar precipitation inputs during these two time periods. Moreover, streamflow in our study catchments is known to be dominated by slow, deep flowpaths (i.e., cool groundwater) due to high permeability sandstone geology of the region (Hale and McDonnell, 2016). Thus, in catchments with less groundwater or hyporheic exchange, the solar radiation that penetrates the RMA and reaches the stream channel may have greater potential to warm stream temperatures.

Single day maximum stream temperatures (T_{MAX}) also did not appear to change following contemporary forest harvesting practices in this location, likely due to similar reasons. The warmest T_{MAX} observed in Needle Branch in the pre-harvest period was 15.7 °C and in the post-harvest period was 14.7 °C, which were both cooler than observations in the unharvested catchment. In comparison, historical forest harvesting (no riparian shade due to complete removal of riparian vegetation) in Needle Branch resulted in an increase in the T_{MAX} from 13.9 °C in the pre-harvest period (1959–1965) to 21.7 °C (1966) and 29.4 °C (1967) in the first two post-harvest years (Brown and Krygier, 1970). In the original Alsea Watershed Study, this substantial increase in T_{MAX} following logging, combined with decreases in dissolved oxygen, was believed to be partially responsible for long-term depression in the cutthroat trout population and reduced numbers of early migrating Coho salmon fry (Hall and Lantz, 1969; Hall, 2008). We interpret the contemporary results and the general lack of observed changes in post-harvesting stream temperature in comparison to historical practices to indicate a substantial improvement in riparian buffer effectiveness in protecting streams against temperature increases.

The Hinkle Creek Paired Watershed Study in the foothills of the western Cascades in southern Oregon also reported on stream temperature response to contemporary forest harvesting practices (Kibler et al., 2013). The observations in the harvested catchments at Hinkle Creek are most comparable to the sub-catchment upstream of NB7 in this study, given that they were also drained by small non-fish bearing tributaries that did not require streamside tree retention under the Oregon Forest Practices Act. Despite the lack of riparian area, the annual T_{MAX} ranged from 2.1 °C cooler to 1.1 °C warmer in the harvested catchments, relative to pre-harvest years (Kibler et al., 2013). The observed cooling was attributed to shading provided by a layer of logging slash that was deposited over the streams during harvesting, and to increased summer baseflows, similar to Needle Branch. In a broader analysis of stream temperature data from 33 sites in the Oregon Coast Range, average summer T_{MAX} increased by ~0.7 °C (range: −0.9 to 2.5 °C) in small and medium private forest streams adjacent to cutblocks with 15 m and 21 m RMAs, respectively (Groom et al., 2011). While these changes in stream temperature were also an improvement over historic management practices, similar to our study, Groom et al. (2011) also showed that state forest streams, which require wider buffers, were more effective at maintaining stream temperatures similar to reference conditions. Similarly, other recent studies in the Pacific Northwest have observed increases in T_{MAX} of 0.2–2.4 °C following contemporary forest harvesting (Gomi et al., 2006; Pollock et al., 2009; Janisch et al., 2012).

In the present study there was also little evidence that diel stream temperature (T_{DIEL}) changed after forest harvesting (Table 5). Average T_{DIEL} decreased by ~0.2 °C at both the uppermost (NB7) and lower (NB2) stream reaches in Needle Branch after harvesting; however, T_{DIEL} increased ~0.1 °C at the middle reach (NB6), which is at the outlet of the cutblock. Alternatively, T_{DIEL} decreased by ~0.4 °C across all of the reference catchment sites over the same time period (Fig. 8). While this could be evidence for greater day-to-day variability in stream temperature following forest harvesting at Needle Branch the difference in T_{DIEL} from the pre- to the post-harvest period was not statistically significant when compared with paired sites in Flynn Creek. Moreover, this observation is counter to the original Alsea Watershed Study as maximum T_{DIEL} increased considerably in the harvested catchment, Needle Branch, by ~12.3 °C from the pre-harvest years to the post-harvest years (3.3–15.6 °C), while decreasing ~0.5 °C (3.9–3.4 °C) in Flynn Creek over that same period (Brown and Krygier, 1970; Moring, 1975). Recent studies have shown more variable responses in T_{DIEL} trends, with some trends higher, some lower, and some unchanged (Groom et al., 2011; Cole and Newton, 2013). Given that diel fluctuations have the potential to influence aquatic organisms whose growth is regulated by temperature (Hokanson et al., 1977; McCullough et al., 2009), contemporary forest harvesting practices appear to be much more effective than historical practices at maintaining thermal stability after forest harvest, with concomitant maintenance of aquatic ecosystem health.

5. Conclusions

This unique study, allowed us to re-visit the same research catchments that were harvested and studied in the 1960s to investigate how the shade provided by riparian management areas—required by 21st century forest management practices—mitigated stream temperature warming following forest harvesting. Our study indicates that the enhancements in stream buffering in Oregon over the past ~50 years can reduce the stream temperature changes that can occur following forest harvesting as compared to historical practices. In comparison to the original Alsea Watershed Study (i.e., no riparian vegetation), the more recent harvesting practices (e.g., retention of riparian vegetation for shade provision) appear to provide vastly improved protection for stream water temperatures. However, our results need to be interpreted with caution as several factors may have contributed to a more muted stream temperature response to forest harvesting than might occur in other regions, including (a) north-south stream orientation, which would maximize RMA effectiveness, (b) steep catchment and channel slopes that can increase stream velocity and hyporheic exchange, and (c) potential increases in groundwater contributions after harvesting. These factors do not make it possible to interpret our observations as indication that current RMA regulations are broadly effective – beyond Oregon Coast Range catchments with similar geology and physiography – at minimizing stream temperature increases following forest harvesting. For example, research on impacts of contemporary forest harvesting on stream temperature from other regions indicate highly variable responses and remaining opportunities for improved practices. More detailed examination of local RMA and stream channel conditions, such as shade, aspect, slopes, soils, lithology, and groundwater-surface water interactions are needed to decipher the site-specific conditions that are desirable for mitigation of impacts on stream temperature.

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