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# A multicatchment analysis of headwater and downstream temperature effects from contemporary forest harvesting

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## Abstract

Stream temperature is a key physical water-quality parameter, controlling many biological, chemical, and physical processes in aquatic ecosystems. Maintenance of cool stream temperatures during summer is critical for high-quality aquatic habitat. As such, transmission of warm water from small, nonfish-bearing headwater streams after forest harvesting could cause warming in downstream fish-bearing stream reaches with negative consequences. In this study, we evaluate (a) the effects of contemporary forest management practices on stream temperature in small, headwater streams, (b) the transmission of thermal signals from headwater reaches after harvesting to downstream fish-bearing reaches, and (c) the relative role of lithology and forest management practices in influencing differential thermal responses in both the headwater and downstream reaches. We measured summer stream temperatures both preharvest and postharvest at 29 sites—12 upstream sites (4 reference, 8 harvested) and 17 downstream sites (5 reference, 12 harvested)—across 3 paired watershed studies in western Oregon. The 7-day moving average of daily maximum stream temperature ($T_{7DAYMAX}$) was greater during the postharvest period relative to the preharvest period at 7 of the 8 harvested upstream sites. Although the $T_{7DAYMAX}$ was generally warmer in the downstream direction at most of the stream reaches during both the preharvest and postharvest period, there was no evidence for additional downstream warming related to the harvesting activity. Rather, the $T_{7DAYMAX}$ cooled rapidly as stream water flowed into forested reaches ~370–1,420 m downstream of harvested areas. Finally, the magnitude of effects of contemporary forest management practices on stream temperature increased with the proportion of catchment underlain by more resistant lithology at both the headwater and downstream sites, reducing the potential for the cooling influence of groundwater.

KEYWORDS

clear-cut, forest management, geology, headwater stream, riparian buffers, stream temperature

## 1 | INTRODUCTION

Estimating the thermal response of headwater streams and rivers to forest disturbance is increasingly important given current and projected climate change (Luce et al., 2014; Pyne & Poff, 2017) and land use activities (Hester & Doyle, 2011). Forest management activities, such as harvesting near streams, can increase summertime stream temperatures because of reduced shade and increased solar radiation reaching the stream surface (Moore, Spittlehouse, & Story, 2005; Studinski, Hartman, Niles, & Keyser, 2012). Changes in stream temperature regimes are principally a concern when resulting temperatures are outside the range of thermal tolerances for aquatic ecosystem biota (Bear, McMahon, & Zale, 2007; Dunham, Rieman, & Chandler, 2003). Elevated stream temperatures can affect primary productivity (D'Angelo, Gregory, Ashkenas, & Meyer, 1997; Morin, Lamoureux, & Busnarda, 1999), benthic invertebrates (Caruso, 2002; Hawkins, Hogue, Decker, & Feminella, 1997; Hogg & Williams, 1996), fish habitat (Beitinger, Bennett, & McCauley, 2000; Eaton & Scheller, 1996; Ice, 2008; Waite & Carpenter, 2000), and the rates of in-stream chemical processes (Demars et al., 2011).

  

Due to the importance of this physical water-quality parameter, there have been many studies regarding changes in the thermal regimes of streams following forest management activities (Gravelle & Link, 2007; Guenther, Gomi, & Moore, 2014; Kibler, Skaugset, Ganio, & Huso, 2013; Macdonald, MacIsaac, & Herunter, 2003; Moore, Spittlehouse, et al., 2005). Historical studies showed highly elevated stream temperature and aquatic ecosystem impacts after forest harvesting (Beschta, Bilby, Brown, Holtby, & Hofstra, 1987; Brown & Krygier, 1970; Levno & Rothacher, 1967; Moring & Lantz, 1974). These studies led to changes in forest management practices in many states, provinces, and territories in the United States and Canada, which added or increased the requirement for the retention of overstory trees in riparian buffer zones for provision of shade (Hairston-Strang, Adams, & Ice, 2008; Lee, Smyth, & Boutin, 2004). Recent studies investigated the efficacy of contemporary practices and, in particular, the role of stream buffers in mitigating postharvesting changes in stream temperature in either headwater reaches (Gomi, Moore, & Dhakal, 2006; Groom, Dent, Madsen, & Fleuret, 2011; Janisch, Wondzell, & Ehinger, 2012; Kibler et al., 2013; Rex, Maloney, Krauskopf, Beaudry, & Beaudry, 2012) or downstream locations (Cole & Newton, 2013; Reiter, Bilby, & Heffner, 2015; Story, Moore, & Macdonald, 2003). In general, contemporary forest management practices have resulted in less warming of streams relative to historical practices (Bladon, Cook, Light, & Segura, 2016; Gomi et al., 2006; Groom et al., 2011). However, the effectiveness of riparian buffers has varied widely depending on several interacting in situ characteristics such as geology, physiography, and hydrology (Janisch et al., 2012; Pollock, Beechie, Liermann, & Bigley, 2009). For example, daily maximum stream temperatures increases ranged between −0.9 and 2.5 °C (mean increase 0.7 °C) at 18 private forest sites in the Oregon Coast Range following contemporary forest harvesting with riparian buffer zones (15 and 21 m around small and medium fish-bearing streams, respectively; Groom et al., 2011). Comparatively, in western Oregon forests, stream temperature daily maxima increased up to 5.3 °C following contemporary forest harvesting with 15–30 m wide buffers (Cole & Newton, 2013). In Washington, the daily maximum stream temperature increased by 1.1 °C (range: 0.0–2.8 °C) in continuously buffered catchments (Janisch et al., 2012), whereas in coastal British Columbia, the temperature increased 0.0–0.8 °C in streams with 10-m riparian buffers (Gomi et al., 2006).

If headwater streams warm after forest harvesting, there is concern about the downstream transmission of heated water, which would increase the spatial extent of thermal effects on aquatic ecosystems (Moore, Sutherland, Gomi, & Dhakal, 2005). This concern has been reinforced by historical observations of thermal energy inputs being transmitted downstream as cumulative effects (Beschta & Taylor, 1988; Gregory, Swanson, McKee, & Cummins, 1991). For example, all 14 forested headwater streams in a study in western Oregon demonstrated a natural warming trend in the downstream direction (~0.44 °C km$^{-1}$), even under full forest cover (Zwieniecki & Newton, 1999). Similarly, stream temperature warmed by ~0.07–0.10 °C km$^{-1}$ in the downstream direction in larger river systems (Torgersen, Faux, McIntosh, Poage, & Norton, 2001). As such, asymptotic warming is often the supported conceptual paradigm for longitudinal stream temperature patterns (Caissie, 2006; Vannote, Minshall, Cummins, Sedell, & Cushing, 1980). However, the general model of downstream warming likely oversimplifies stream temperature dynamics (Dent, Vick, Abraham, Schoenholtz, & Johnson, 2008; Leach & Moore, 2011). Studies from Oregon, California, British Columbia, and elsewhere have also demonstrated both natural stream cooling in a downstream direction (Fullerton et al., 2015; Madej, Currens, Ozaki, Yee, & Anderson, 2006) and cooling of warmed water flowing from a stream reach draining a clear-cut back into a closed canopy (Keith, Bjornn, Meehan, Hetrick, & Brusven, 1998; McGurk, 1989; Story et al., 2003). Although there is growing recognition of the high degree of variability in longitudinal stream temperature dynamics (Davis, Reiter, & Groom, 2015; Ebersole, Liss, & Frissell, 2003; Fullerton et al., 2015), it is increasingly important to determine the magnitude, spatial extent, and drivers of the downstream transmission of warmer stream water following disturbances.

In this study, we evaluated the downstream stream temperature responses to forest harvesting by integrating data from three paired watershed studies (Trask, Hinkle, and Alsea) in headwater streams of western Oregon. This vast and unique data set includes distributed stream temperature data collected at 27 sites over a period of 14 years. Data collection occurred during preharvest and postharvest years, as well as within and downstream from harvested and unharvested, reference catchments. The study catchments also include a diversity of geology, physiography, and forest management practices (Bywater-Reyes, Segura, & Bladon, 2017; Hale & McDonnell, 2016; Kibler et al., 2013). The objectives of this study were to examine: (a) the effects of contemporary forest management practices on stream temperature in small, headwater streams, (b) whether warmer stream water after harvesting in headwater reaches was detectable in downstream fish-bearing reaches, and (c) the relative role of geology and forest management practices in influencing differential stream temperature responses in both headwater and downstream reaches.

## 2 | METHODS

### 2.1 | Study sites

This research included data from three paired watershed studies in Oregon, USA, including (a) Trask Paired Watershed Study (2008–2015; Figure 1a), (b) Alsea Watershed Study Revisited (2006–2012; Figure 1 b), and (c) Hinkle Paired Watershed Study (2002–2009; Figure 1c). The Trask (elevation: ~275–1,100 m) and Alsea (elevation: ~140–490 m) studies are located in the Coast Range, whereas the Hinkle study is located in the Western Cascades (elevation: ~400–1,250 m). Study catchments are generally steep but include a wide range of mean catchment slopes and aspects (Table 1). Study catchments also encompass a range of geology, including Holocene–Pleistocene landslide deposits, Eocene basalt, Eocene marine sedimentary rocks, Eocene rhyolite/dacite flows, and Eocene volcanolithic sandstones (Table 1).

All three watershed studies have a marine west coast climate, with slight differences in mean annual precipitation between the Trask (2,450–3,500 mm yr$^{-1}$), Alsea (1,900–2,300 mm yr$^{-1}$), and Hinkle (1,500–2,100 mm yr$^{-1}$). Rainfall occurs primarily during winter and spring; summer rainfall is minimal relative to yearly totals (<10% annual

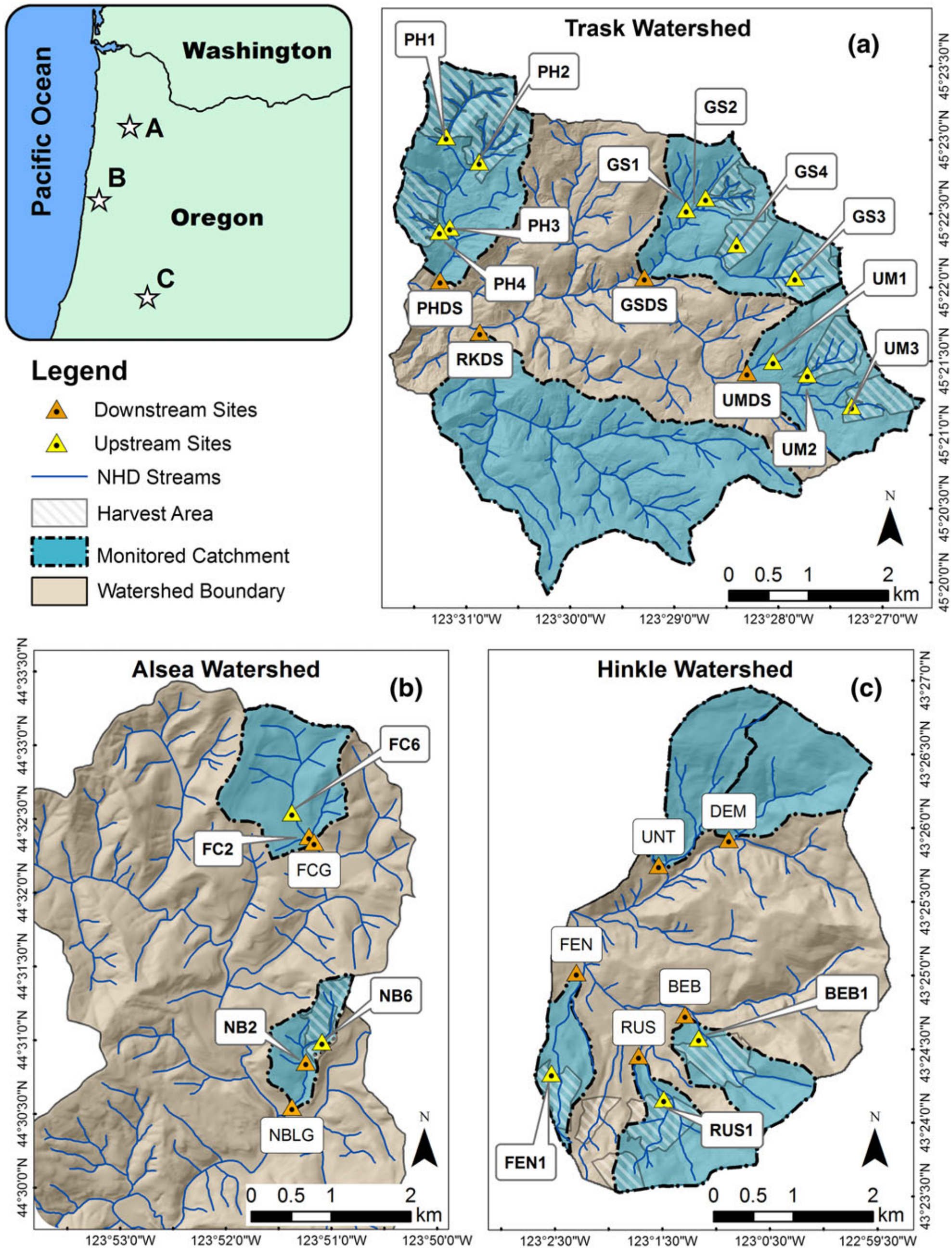


**FIGURE 1** Site map of paired-watershed studies, including (a) Trask paired watershed study, (b) Alsea watershed study revisited, and (c) Hinkle Creek paired watershed study

rainfall; PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed January 26, 2017). This annual rainfall pattern leads to streamflow dominated by baseflow in late July and August.

Over the period of study, the mean daily air temperature during July and August ranged from 16.0 to 18.0 °C at the Trask and Alsea catchments. It was slightly warmer, ranging from 18.0 to 20.0 °C at the Hinkle watersheds. September air temperatures were cooler than the summer temperatures at all study sites. The mean daily air temperatures at the Trask and Alsea watersheds ranged between 15.0 and 16.5 °C, whereas mean daily air temperatures at the Hinkle watersheds ranged between 16.5 and 18.0 °C.

At the larger downstream watershed-scale, all three studies contain fish-bearing stream reaches, supporting resident and anadromous fish species. The Trask Watershed Study is primarily populated by Coho salmon (*Oncorhynchus kisutch*), coastal cutthroat trout (*Oncorhynchus clarkii clarkii*), steelhead trout (*Oncorhynchus mykiss*), and reticulate sculpin (*Cottus perplexus*), which are principally in the mainstem and lower reaches of Pothole Creek (Penaluna et al., 2015). Fish species at the Alsea include Coho salmon, coastal cutthroat trout, western brook lamprey (*Lampetra richardsoni*), Pacific lamprey (*Larrea tridentata*), and reticulate sculpins (Hall, 2008). At the Hinkle, coastal cutthroat trout were the principal fish species (Berger & Gresswell, 2009).

Tree species in all three study areas mainly consist of Douglas-fir (*Pseudotsuga menziesii)* with red alder (*Alnus rubra*) principally in the riparian areas. Some western hemlock (*Tsuga heterophylla)* and western red cedar (*Thuja plicata*) are found in the Hinkle study area (Kibler et al.,

**TABLE 1** Descriptive information for the 29 observation sites

| Study | Catchment | Site | Thalweg distance from harvest boundary (m)[a] | Area (ha) | Geology[b] | % sedimentary + landslide + volcaniclastics (friability) | Aspect/mean slope (°) | Harvest method (% area)[c] | Streamside vegetation retention |
|---|---|---|---|---|---|---|---|---|---|
| Alsea | Flynn | FC6 | | 153.0 | Ty | 100 | S/16.6 | Reference | |
| | | FC2 | | 210.0 | Ty | 100 | S/16.6 | Reference | |
| | | FCG | | 210.5 | Ty | 100 | S/16.2 | Reference | |
| | Needle | NB6 | −210 | 28.0 | Ty | 100 | S/18.1 | CC (89) | 15 m |
| | | NB2 | 210 | 62.0 | Ty | 100 | S/18.1 | CC (60) | |
| | | NBLG | 800 | 85.8 | Ty | 100 | S/17.5 | CC (41) | |
| Hinkle | Beebe | BEB1 | 20 | 113.4 | Tbf | 0 | NW/25.5 | CC (31) | Slash present |
| | | BEB | 370 | 127.7 | Tbf | 4 | N/24.8 | CC (33) | |
| | Fenton | FEN1 | 20 | 28.8 | Qls | 100 | N/15.9 | CC (65) | Slash present |
| | | FEN | 1420 | 99.5 | Qls | 100 | N/12.6 | CC (27) | |
| | Russell | RUS1 | 15 | 148.6 | Qls, Tbf | 7 | NW/19.3 | CC (10) | Slash present |
| | | RUS | 685 | 168.0 | Qls, Tbf | 25 | N/19.1 | CC (27) | |
| | DeMerssemon | DEM | | 195.4 | Tbf, Tvs, Tsf | 14 | SW/21.2 | Reference | |
| | Unnamed | UNT | | 193.2 | Tbf, Tsf, Tvs | 30 | S/14.3 | Reference | |
| Trask | Gus | GS3 | −280 | 37.8 | Tidb | 0 | W/20.7 | CC (94) | None |
| | | GS4 | −270 | 37.8 | Tidb | 0 | SW/18.1 | CC (91) | None |
| | | GS2 | 40 | 39.0 | Tidb, Ty | 1 | SW/21.5 | Thin (29) | 20 m |
| | | GS1 | | 26.6 | Tidb, Ty | 5 | S/17.5 | Reference | |
| | | GSDS | 1100 | 302.2 | Tidb, Tsbr, Ty | 12 | W/18.5 | Clear-cut (30) | |
| | Pothole | PH1 | −50 | 67.1 | Tib, Tbr | 46 | S/18.9 | CC (40), RC (37) | 17 m |
| | | PH4 | −40 | 26.4 | Qls, Trsk, Tsbr, Tib | 99 | Se/17.1 | Modified CC (92) | 12 m |
| | | PH2 | −25 | 45.0 | Tbr, Ty, Qls | 100 | S/24.6 | Modified CC (78) | 11 m |
| | | PH3 | | 48.5 | Qls, Tsbr, Ty, Tsbr | 92 | W/17.2 | Reference | |
| | | PHDS | 780 | 324.6 | Qls, Tib, Tbr, Trsk, Tsbr | 56 | S/19.4 | CC (45) | |
| | Upper Mainstem | UM3 | −70 | 39.1 | Ty, Tidb | 60 | W/11.5 | CC (56) | 8 m, 60% of stream |
| | | UM2 | −55 | 37.6 | Ty, Tidb | 60 | SW/14.8 | CC (83) | 8 m, 25% of stream |
| | | UM1 | | 44.5 | Ty, Tidb | 0 | W/17.1 | Reference | |
| | | UMDS | 990 | 278.8 | Qls, Tidb, Ty | 58 | W/13.6 | CC (27) | |
| | Rock | RKDS | | 669.5 | Qls, Tidb, Tsbr, Ty | 42 | N, NW/17.9 | Reference | |

[a]A negative number indicates that the site is located within the harvested unit.

[b]Qls: Holocene–Pleistocene landslide deposits; Tbf, Tbr, Tib, Tidb, Tsbr: Eocene basalt; Trsk, Ty: Eocene marine sedimentary; Tsf: Eocene rhyolite/dacite flows; Tvs: Eocene volcanolithic sandstone.

[c]CC: clear-cut; RC: retention cut.

2013). The distribution of red alder varied throughout the study catchments as a function of elevation and precipitation. At the higher elevation, drier Hinkle catchments, red alder was primarily found as understorey vegetation within riparian areas. However, at the lower elevation, wetter catchments of the Trask and Alsea studies, red alder was more abundant and spatially distributed.

Within each watershed study, the subcatchments were either harvested or remained as unharvested, reference catchments. Timber harvesting operations, area harvested, and riparian buffer zone practices varied among the watershed studies and between individual sites (Table 1). At the Trask study, forest harvesting of the upstream catchments covered ~90–97% of the catchment area above the observation points at the catchment outlets. Retention of vegetation in streamside riparian areas varied from no vegetation to an average buffer width of 20 m along some stream reaches (Table 1). At the Alsea study, ~89% of the catchment area above the headwater site (NB6) was clear-cut with an average riparian buffer width of ~15 m along the entire stream, except for three small, nonfish-bearing tributaries located upstream of a waterfall. At the Hinkle study, the clear-cut area varied by site from 10% to 65% (Table 1)—there was no retention of riparian vegetation adjacent to the nonfish-bearing streams. However, a layer of logging slash remained directly over the streambeds following the removal of merchantable timber.

## 2.2 | Stream temperature data collection

Stream temperature instrumentation was deployed each year in all three watershed studies to collect data during the summer low-flow period (July–September). Data were collected both preharvest and postharvest at all sites—data collected during the summer of harvesting activity was included as postharvest data to capture any immediate or short-term changes in stream temperature. Across the three study watersheds, there were 29 sites where stream temperature was measured—12 upstream sites (4 reference, 8 harvested) and 17 downstream sites (5 reference, 12 harvested). The downstream sites ranged from 15- to 1,420-m thalweg distance downstream from the lower harvest boundary (harvested sites) or from the most upstream thermistor (reference sites; Table 1).

We measured stream temperature with HOBO Water Temp Pro v2 data loggers (Onset HOBO model U22–001, ±0.2 °C) at the Trask study and Onset TidbiT water temperature data loggers (Onset model UTBI-001, ±0.21 °C) at the Alsea study. At the Hinkle study, we measured stream temperature with HOBO Water Temp Pro data loggers (Onset HOBO model H20–001, ±0.2 °C) at the upstream sites and with a specific conductivity probe (Campbell Scientific CS547A sensor, ±0.1 °C) at the downstream sites.

## 2.3 | Statistical analysis

The metric selected for stream temperature analysis was the 7-day moving average of daily maximum stream temperature ($T_{7DAYMAX}$). We selected this metric because it (a) is biologically more meaningful than mean daily stream temperature, (b) is not overly influenced by the maximum temperature of a single day, and (c) may be used to assess both sublethal chronic and acute temperature exposure in fish (McCullough, Spalding, Sturdevant, & Hicks, 2001). The objectives of the statistical analysis were to assess (a) whether the $T_{7DAYMAX}$ changed from the preharvest period to the postharvest period in the headwater sites and (b) if postharvest changes in $T_{7DAYMAX}$ in the headwater sites were detectable at downstream sites. We also performed regression analysis to determine the relative relationship between percent catchment harvested and catchment lithology on the maximum daily stream temperature response at the downstream and upstream, headwater sites.

To detect whether $T_{7DAYMAX}$ changed from the preharvest to the postharvest period, we paired harvested sites with a reference site based on spatial proximity (within subwatersheds and within each watershed study), similarity of site longitudinal position relative to the harvest boundary, and catchment geology and physiography. We did this for all upstream, headwater sites (Objective 1) and downstream sites (Objective 2), resulting in 20 harvest sites (8 upstream, 12 downstream) paired with reference sites.

We then generated statistical models from each of these harvest site and reference site pairs. We first formulated models from the preharvest relation of $T_{7DAYMAX}$ between each harvest–reference site pair to predict the expected stream temperature in the harvested stream reaches during the postharvest period. Then, we compared observations of $T_{7DAYMAX}$ within and downstream of the harvested catchments during the postharvest period to both the model predicted values and the 95% prediction intervals (PIs). PIs were calculated to capture both the variability of the response variable and that of the model itself.

We interpreted stream temperature observations outside (above or below) of the 95% PI in the postharvest period as being outside of the model-expected range and refer to these observations as statistical "exceedances," suggesting an impact of forest harvesting (Figure 2). Expected values that were above the mean model prediction, but remained within the 95% PI, were classified as "elevated" values (Figure 2). Elevated values provided insight into stream temperature increases that may not have been large enough to be detected as exceedances but may have been elevated in relation to the preharvest period.

Models were generated using generalized least squares (GLS) regression with sine and cosine terms to represent the pattern of stream temperature over each measurement period (seasonal autocorrelation). Autoregressive moving average (ARMA) terms accounted for temporal autocorrelation of observations (dependence of a stream temperature observation on previous observations). ARMA terms ($p$, $q$) were allowed to vary from $(0, 0) \le (p, q) \le (4, 4)$. The partial autocorrelation function (MA terms), autocorrelation function (AR terms), and residual plots (model stationarity) were reviewed to ensure that the autocorrelation was correctly accounted for and that the model residuals exhibited stationarity (Clinton, 2011; Guenther et al., 2014; Som, Zègre, Ganio, & Skaugset, 2012). The optimal overall model was selected using Akaike information criterion (Akaike, 1974). The statistical models were executed using the *gls* function in the *nlme* package in R (Pinheiro & Bates, 2000). The 95% PIs were calculated using the *mvrnorm* function in the *MASS* package (Bolker, 2008; Venables & Ripley, 2002), whereas the predictions were generated using the *predict* function in base R (R Core Team, 2016).

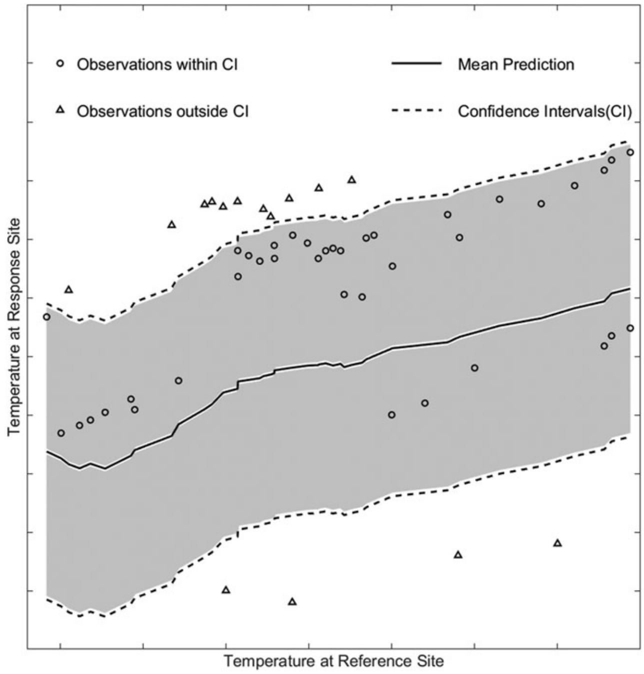


**FIGURE 2** Example of model developed for each site pair (reference site compared to harvested site) to statistically detect changes in the $T_{7DAYMAX}$ from the preharvest to the postharvest period. The mean predicted value and 95% prediction intervals were generated from the preharvest relation of $T_{7DAYMAX}$ between each reference-harvest site pair. Postharvest observations in the harvested site that were above the model predicted value (circles) were classified as "elevated," whereas observations that were outside the 95% prediction interval were classified as "exceedances" (triangles) as these were $T_{7DAYMAX}$ greater or less than would be expected based on the preharvest relationship

## 3 | RESULTS

Basic descriptive statistics indicated that the median of the 7-day moving average of daily maximum stream temperature ($T_{7DAYMAX}$) was greater at seven of the eight harvested upstream sites (all except NB6) during the postharvest period relative to the preharvest period (Figure 3). We observed the largest increases at harvested sites within the Trask Paired Watershed Study—the median $T_{7DAYMAX}$ had warmed by 3.9 °C at GS3, 3.4 °C at GS4, 3.3 °C at UM3, and 2.4 °C at UM2 during the postharvest period (Figure 3).

Model results were generally in agreement with raw observations and descriptive statistics. Across all postharvest years, the observed $T_{7DAYMAX}$ was elevated above the upper bounds of the 95% PI at seven of the eight harvested, headwater sites (Table 2). During the postharvest years, we observed the $T_{7DAYMAX}$ outside the bounds of the 95% PI on 201–340 occasions (22–100% of the time) in each of GS3, GS4, UM3, and UM2 (Table 2). In GS3 and UM3, the largest exceedances of $T_{7DAYMAX}$ above the 95% PI occurred in the first year after harvest but diminished in the second and third years (Table 3). Comparatively, the $T_{7DAYMAX}$ remained elevated in GS4 through the third postharvest year (Table 3).

Smaller increases in $T_{7DAYMAX}$ were observed during the postharvest period at three upstream sites, PH1, PH2, and PH4. During the postharvest period, the median $T_{7DAYMAX}$ only warmed by 1.0 °C at PH4, 0.8 °C at PH1, and 0.6 °C at PH2 (Figure 3). The model results indicated that the observed $T_{7DAYMAX}$ was elevated above the upper bounds of the 95% PI during the postharvest years on 29 occasions in PH4 (0–13% of the annual observations), 26 occasions in PH1

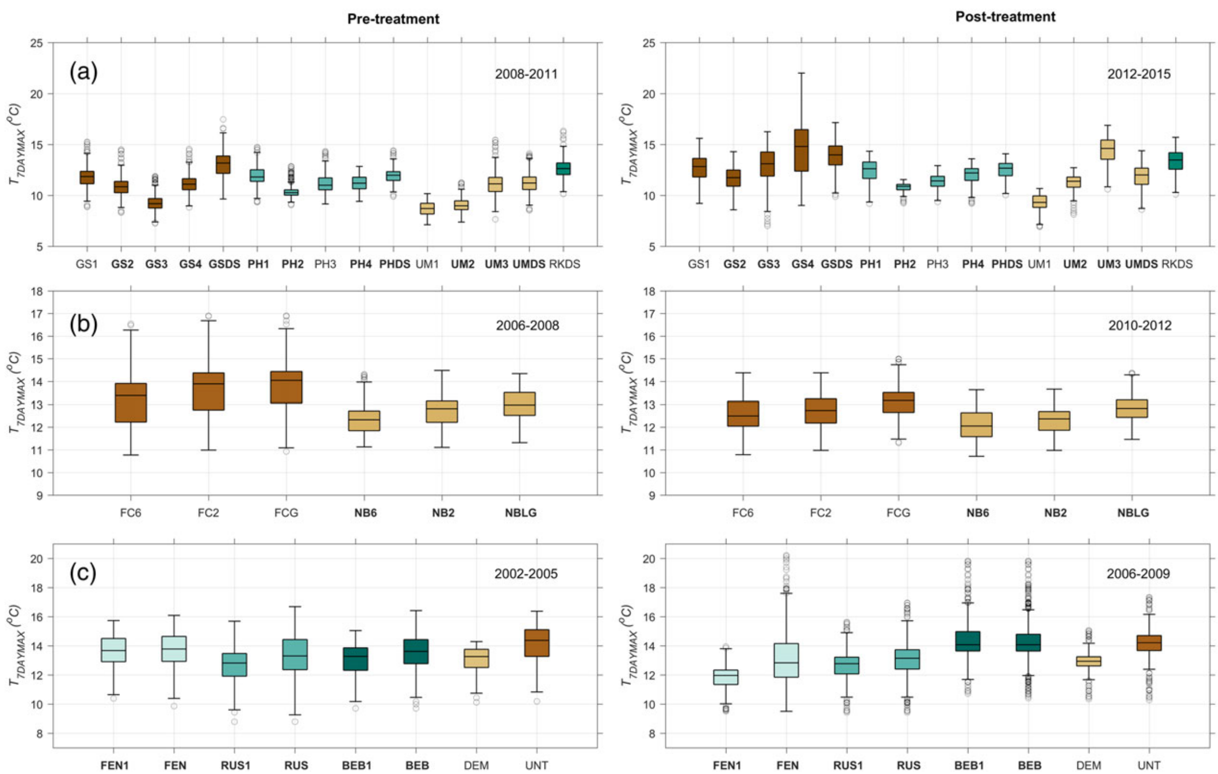


**FIGURE 3** Boxplots of observed $T_{7DAYMAX}$ from the preharvest to the postharvest periods in (a) Trask paired watershed study, (b) Alsea watershed study revisited, and (c) Hinkle Creek paired watershed study

**TABLE 2** Mean $T_{7DAYMAX}$ increase above model predictions for elevated values (above predicted value: PV) and exceedances (above 95% prediction interval: PI) for upstream sites located within harvested catchments and downstream sites located below harvested catchments

| Site type | Site | Location[a] (m) | $T_{7DAYMAX}$ mean above PV and PI (°C) Elevated[b] | *n* | Exceedance[c] | *n* |
|---|---|---|---|---|---|---|
| Upstream | GS3 | −280 | 0.6 | 24 | 3.1 | 340 |
| | GS4 | −270 | 0.3 | 72 | 3.3 | 201 |
| | NB6 | −210 | 0.3 | 235 | 1.2 | 85 |
| | UM3 | −70 | 0.5 | 62 | 3.0 | 302 |
| | UM2 | −55 | 0.3 | 30 | 1.5 | 334 |
| | PH1 | −50 | 0.4 | 338 | 1.5 | 26 |
| | PH4 | −40 | 0.6 | 335 | 1.8 | 29 |
| | PH2 | −25 | 0.4 | 348 | | 0 |
| Downstream | RUS1 | 15 | 0.1 | 184 | | 0 |
| | BEB1 | 20 | 0.5 | 15 | 1.0 | 223 |
| | FEN1 | 20 | | 184 | | 0 |
| | GS2 | 40 | 0.1 | 76 | | 0 |
| | NB2 | 210 | 0.2 | 308 | 1.0 | 12 |
| | BEB | 370 | 0.1 | 237 | 0.7 | 1 |
| | RUS | 685 | 0.2 | 184 | | 0 |
| | PHDS | 780 | 0.1 | 356 | 0.5 | 9 |
| | NBLG | 800 | 0.3 | 183 | | 0 |
| | UMDS | 990 | 0.1 | 365 | | 0 |
| | GSDS | 1100 | 0.1 | 364 | | 0 |
| | FEN | 1420 | 0.1 | 184 | | 0 |

[a]Distance from downstream boundary of forest harvest; negative values indicate locations inside cut block.

[b]Mean of observations above the PV but within the 95% PI.

[c]Mean of observations above the 95% PI.

(0–15% of the annual observations), and was never outside of the 95% PI in PH2 (Table 2).

Despite the increases in $T_{7DAYMAX}$ at many of the upstream, harvested sites after forest harvesting, there was little evidence of increased temperatures in the downstream sites during the postharvest period (Figure 4). Stream temperatures were generally warmer in the downstream direction at most of the stream reaches during both the preharvest and postharvest period; however, evidence for additional downstream warming related to the harvesting activity was minimal. For example, during the preharvest period, the median $T_{7DAYMAX}$ at the upstream sites in Pothole was 11.1 °C, whereas at the downstream site (PHDS), it was 12.0 °C. During the postharvest period, the median $T_{7DAYMAX}$ at the upstream sites in Pothole rose to 11.8 °C, while rising to 12.7 °C at the site ~780 m downstream from the harvesting activity (PHDS). Similarly, the median $T_{7DAYMAX}$ during the preharvest period was 0.9 °C warmer at a site (BEB), which was about 350 m downstream from BEB1. However, during the postharvest period, the median $T_{7DAYMAX}$ was the same (14.1 °C) at both sites, warming slightly at the upstream site while cooling at the downstream site. Similarly, within the Needle Branch, Russel, and Fenton catchments, median $T_{7DAYMAX}$ were slightly warmer in the downstream direction, with no evidence of additional downstream warming following the forest harvesting (Figure 4 and Table 2).

The largest increases in median $T_{7DAYMAX}$ at the downstream sites during the postharvest period were at GSDS and UMDS. These two

**TABLE 3** Mean $T_{7DAYMAX}$ temperature increase above model predictions for elevated values (above PV) and exceedances (above PI) as well as the percentage of observations in each classification per year

| Site | Location[a] (m) | Mean elevated (°C)[b] Year since harvest 0 | 1 | 2 | 3 | Mean exceedance (°C)[c] 0 | 1 | 2 | 3 | % elevated[b] Year since harvest 0 | 1 | 2 | 3 | % exceedance[c] 0 | 1 | 2 | 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GS3 | −280 | 0.1 | | | 0.9 | 3.0 | 3.8 | 3.7 | 1.4 | 3 | 0 | 0 | 16 | 89 | 100 | 100 | 84 |
| GS4 | −270 | 0.3 | nd | | | 1.3 | nd | 3.1 | 3.9 | 72 | nd | 0 | 0 | 22 | nd | 100 | 100 |
| NB6 | −210 | 0.6 | 0.7 | 0.0 | 0.2 | 1.2 | 1.1 | | | 28 | 66 | 9 | 58 | 72 | 34 | 0 | 0 |
| UM3 | −70 | | 0.7 | | 0.5 | 3.2 | 3.7 | 2.6 | 1.6 | 0 | 7 | 0 | 47 | 100 | 93 | 100 | 37 |
| UM2 | −55 | | | 0.5 | 0.2 | 1.4 | 1.8 | 1.3 | 1.1 | 0 | 0 | 3 | 30 | 100 | 100 | 97 | 70 |
| PH1 | −50 | 0.1 | 0.2 | 0.7 | 0.5 | | | 1.2 | 1.9 | 24 | 63 | 85 | 72 | 0 | 0 | 15 | 13 |
| PH4 | −40 | 0.2 | 0.7 | 0.6 | 0.9 | | 1.8 | 1.8 | 1.8 | 58 | 87 | 92 | 88 | 0 | 13 | 7 | 12 |
| PH2 | −25 | 0.1 | 0.5 | 0.5 | 0.3 | | | | | 87 | 100 | 100 | 96 | 0 | 0 | 0 | 0 |
| RUS1 | 15 | nd | 0.0 | 0.2 | nd | nd | | | nd | nd | 34 | 63 | nd | nd | 0 | 0 | nd |
| BEB1 | 20 | nd | 0.5 | 0.5 | | nd | 0.8 | 1.1 | 1.0 | nd | 9 | 9 | 0 | nd | 91 | 91 | 100 |
| FEN1 | 20 | nd | | | nd | nd | | | nd | nd | 0 | 0 | nd | nd | 0 | 0 | nd |
| GS2 | 40 | 0.1 | 0.1 | 0.0 | 0.1 | | | | | 21 | 8 | 7 | 49 | 0 | 0 | 0 | 0 |
| NB2 | 210 | 0.4 | 0.2 | 0.1 | 0.2 | 1.0 | | | | 87 | 96 | 55 | 55 | 13 | 0 | 0 | 0 |
| BEB | 370 | nd | 0.1 | 0.2 | 0.1 | nd | | | 0.7 | | 70 | 86 | 71 | | 0 | 0 | 1 |
| RUS | 685 | nd | 0.0 | 0.1 | nd | nd | | | nd | nd | 21 | 15 | nd | nd | 0 | 0 | nd |
| PHDS | 780 | 0.0 | 0.1 | 0.2 | 0.2 | | | 0.5 | | 10 | 59 | 67 | 100 | 0 | 0 | 10 | 0 |
| NBLG | 800 | 0.2 | 0.3 | 0.1 | 0.3 | | | | | 37 | 91 | 38 | 49 | 0 | 0 | 0 | 0 |
| UMDS | 990 | 0.0 | 0.0 | 0.1 | 0.3 | | | | | 17 | 28 | 71 | 78 | 0 | 0 | 0 | 0 |
| GSDS | 1100 | 0.3 | 0.0 | 0.0 | 0.0 | | | | | 73 | 41 | 5 | 20 | 0 | 0 | 0 | 0 |
| FEN | 1420 | nd | 0.0 | 0.1 | nd | nd | | | nd | nd | 36 | 51 | nd | nd | 0 | 0 | nd |

*Note*. "nd" indicates years without data, and "-" indicates years with data but no observations in the category. PI = prediction interval; PV = predicted value.

[a]Distance from downstream boundary of forest harvest; negative values indicate locations inside cut block.

[b]Mean of observations above the PV but within the 95% PI.

[c]Mean of observations above the 95% PI.

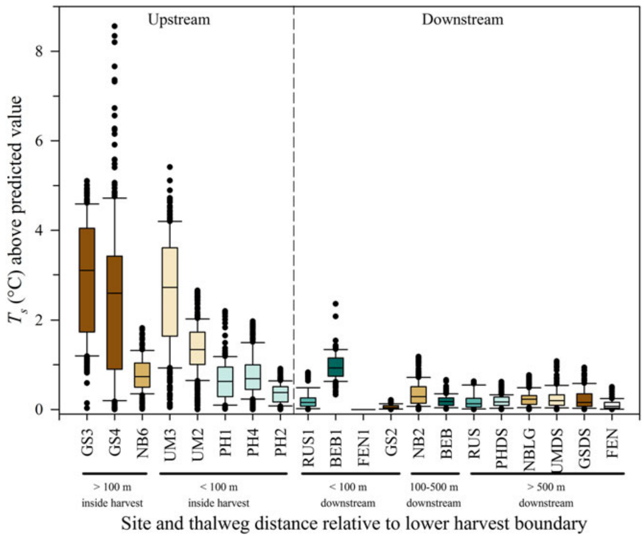


**FIGURE 4** Box plots of observed $T_{7DAYMAX}$ values above the model-predicted values in the postharvest period. Sites ordered on the x-axis by thalweg distance upstream/downstream from the lower harvest boundary

sites received water from the four upstream sites that had the greatest warming following forest harvesting (i.e., GS3, GS4 and UM3, UM2). During the postharvest period, the median $T_{7DAYMAX}$ had warmed by only 0.8 °C at GSDS and 0.8 °C at UMDS. Again, it is important to note that although the raw observations appeared to indicate a slight warming at these downstream sites, the postharvest period was slightly warmer ($T_{air}$ ~1.1 °C) than the preharvest period at these sites. As such, we also observed increases in the median $T_{7DAYMAX}$ at the two upstream, reference subcatchments that drained into GSDS and UMDS—GS1 increased 1.0 °C and UM1 increased 0.6 °C in the postharvest period. The model was again consistent with the observed temperatures, indicating that there were no postharvest measurements of the $T_{7DAYMAX}$ above what would be predicted (outside the 95% PI) at these two downstream sites, GSDS and UMDS (Table 2).

Finally, the magnitude of change in stream temperature and transmission of warmer water downstream were a function of both the percentage of catchment harvested and the underlying geology (Figure 5), but the dominant factor was scale dependent. At the upstream, harvested sites, there was strong evidence that the maximum stream temperature response was related to the catchment lithology ($t$ = −3.45, $p$ = .01). The greatest stream temperature responses to forest harvesting were observed in catchments underlain by resistant lithologies compared to catchments underlain by more erodible, and likely more permeable, lithologies (Figure 5b). Surprisingly, there was no statistical evidence that the maximum stream temperature response at the upstream, harvested sites was dependent on the percent of catchment harvested ($t$ = 0.92, $p$ = .39; Figure 5a). Comparatively, at sites downstream from harvested areas, there was strong evidence that the stream temperature response to forest harvesting was influenced by the interaction between percent of catchment harvested and the underlying lithology ($t$ = −3.05, $p$ = .01). At these downstream sites, the greatest stream temperature responses to forest harvesting were in catchments with a higher proportion of area harvested and were underlain by resistant lithologies.

## 4 | DISCUSSION

The 7-day moving average of maximum daily stream temperature ($T_{7DAYMAX}$) increased in several of the small, nonfish-bearing, headwater streams after contemporary forest harvesting (Figure 3). We observed the greatest increases in the $T_{7DAYMAX}$ at the headwater sites with no riparian buffer around nonfish-bearing stream reaches (e.g., GS3 and GS4) or at the sites with a narrow buffer retained around only a portion of the stream (e.g., UM3 and UM2). We observed an increase in median $T_{7DAYMAX}$ of 2.4–3.9 °C at these sites, similar to other observed increases in maximum daily stream temperatures in the PNW where minimal or no riparian buffers were retained (Gomi et al., 2006; Groom et al., 2011; Groom, Johnson, Seeds, & Ice, 2017; Moore, Sutherland, et al., 2005). This is consistent with increased energy exchange at the stream-air interface on unshaded or partially shaded stream reaches (Brown, 1969; Moore, Sutherland, et al., 2005). There were much smaller or no increases in $T_{7DAYMAX}$ when streams were well shaded due to more consistent retention of a riparian buffer (e.g., PH1, PH2, PH4, and NB6). There have also been many studies illustrating the

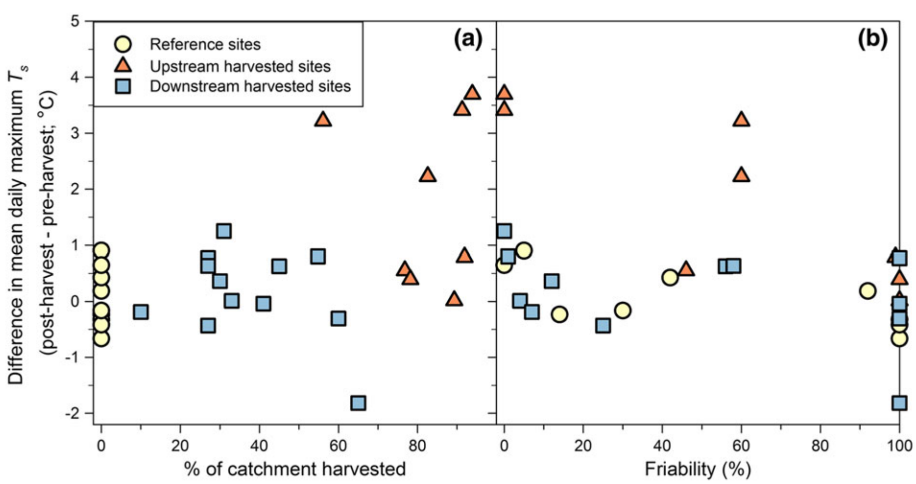


**FIGURE 5** Difference in mean daily maximum stream temperature (July–September) between the postharvest period and the preharvest period relative to (a) percentage of the catchment harvested and (b) the friability of the catchment geology

effectiveness of riparian buffers at mitigating the effects of contemporary forest harvesting activity on stream temperatures (Bladon et al., 2016; Groom et al., 2017; Reiter et al., 2015), which our results support. Despite the known efficacy of riparian buffers, regulations in many regions still allow harvesting without retention of buffers around nonfish-bearing stream reaches (Lee et al., 2004).

However, there remain many uncertainties about whether postharvest warming of headwater stream reaches affect stream temperatures in downstream, fish-bearing reaches. In this study, there was no evidence for substantial transmission of warmer stream water to the downstream, fish-bearing, stream reaches despite warming in some nonfish-bearing stream reaches after harvesting (Figure 4). Most of the stream reaches had slightly warmer stream temperatures in the downstream direction, but this occurred during both the preharvest and postharvest period, a tendency that has been previously illustrated in western Oregon (Zwieniecki & Newton, 1999). However, there was no evidence for additional downstream warming related to the harvesting activity. Rather, heated water from harvested sites such as GS3, GS4, UM3, and UM2 rapidly decreased in temperature after flowing into stream reaches with full forest cover. For example, at sites ~990–1,100 m downstream of these reaches, there was no detectable change in $T_{7DAYMAX}$. Similarly, there was no evidence for additional downstream warming, which could be attributed to forest harvesting, at sites 370–1,420 m downstream (i.e., BEB, RUS, PHDS, NBLG, and FEN; Table 2). These insights are important because research into the downstream propagation of warmer water after forest harvesting at the small headwater catchment scale has been limited. Moreover, it has previously been suggested that once a stream's temperature was increased, the heat would not be readily dissipated even if the stream flowed through a shaded reach (Beschta et al., 1987). Several observations since then, including those presented herein, have illustrated that maximum stream temperature may decrease rapidly after flowing out of a clear-cut, or other opening, and into a shaded stream reach (Johnson, 2004; Malcolm, Hannah, Donaghy, Soulsby, & Youngson, 2004; Torgersen, Price, Li, & McIntosh, 1999; Zwieniecki & Newton, 1999). Several studies have documented cooling gradients of warmed water flowing downstream from openings into reaches with closed forest canopies; however, the magnitude of cooling effects have been highly variable, ranging from 2.0 to 9.2 °C km$^{-1}$ (Broadmeadow, Jones, Langford, Shaw, & Nisbet, 2011; Keith et al., 1998; Story et al., 2003). Davis et al. (2015) used Newton's law of cooling to develop an empirical model, which estimated that maximum stream temperature would decline ~50% at a distance ~300 m downstream from a harvest. They attributed the principal determinants of variability in the actual cooling gradient to the downstream width, depth, and channel gradient (Davis et al., 2015). However, their model did not explicitly consider groundwater contributions, hyporheic exchange, or the potential cooling effect from incoming tributaries.

In this study, we were able to attribute some of the variability in maximum daily stream temperature response, both within and across the three watershed studies, to differences in the underlying lithology. At the upstream harvested sites, the greatest differences in maximum daily stream temperature between the preharvest and postharvest period were generally in catchments underlain by more resistant lithologies (e.g., GS3, GS4, UM2, and UM3; Figure 5b). In these streams, the thermal regime was likely controlled by the solar radiation incident on the stream surface, rather than subsurface heat exchange (Johnson, 2004). In stream reaches with low-permeability lithology, Garner, Malcolm, Sadler, and Hannah (2014) also attributed stream temperatures and longitudinal cooling gradients principally to energy exchange at the water-column–atmosphere interface.

Comparatively, the smallest responses in maximum daily stream temperature between the preharvest and postharvest period were generally in headwater catchments underlain by more permeable lithologies (e.g., NB6, PH2, and PH4; Figure 5b). This relationship is likely related to the role of geology as a primary driver of the proportion of streamflow dominated by surface water or groundwater and subsurface flow (Mayer & Naman, 2011). In general, the proportion of streamflow dominated by groundwater increases in more permeable geology (Hale & McDonnell, 2016; Tague & Grant, 2004). Groundwater is typically cooler and thermally stable compared to surface water or near-surface water during the summer, which can moderate temperature extremes by decreasing a stream's sensitivity to energy inputs (Constantz, 1998; Mellina, Moore, Hinch, Macdonald, & Pearson, 2002; Moore & Wondzell, 2005; Wagner et al., 2014). Although deeper, longer groundwater flowpaths would strengthen this effect, Guenther et al. (2014) have also demonstrated that shallow groundwater can provide a cooling influence on summer stream temperatures and moderate the impacts of forest harvesting.

Comparisons of the stream temperature response to forest harvesting between the upstream and downstream sites illustrate the complexity and challenge of developing a unifying model of downstream temperature change. At all scales, lithology was an important factor, modulating the stream temperature response. For example, two sites (NB2 and FEN1) that had some of the greatest percentage of upstream area harvested were actually cooler in the postharvest period relative to the preharvest period. Both sites were underlain by permeable Oregon Coast Range sedimentary bedrock or landslide deposits, which are a dominant control on groundwater storage, hyporheic exchange, and streamflow (Hale & McDonnell, 2016). The muted streamflow response in catchments with a higher percentage area harvested may also be attributable to increases in summer low flows associated with reduced evapotranspiration (Surfleet & Skaugset, 2013). Together, groundwater dynamics and increased volume of flow may act to insulate and buffer stream temperatures (Poole & Berman, 2001). Comparatively, two sites (GS2 and BEB1) with a relatively small percentage of catchment harvested were warmer in the postharvest period relative to the preharvest period. However, low-permeability lithology underlay these catchments—as such, the stream water may be have been more tightly coupled to atmospheric energy inputs, whereas the smaller area harvested may have had less impact on summer low flows.

## 5 | CONCLUSIONS

In this study, we observed elevated maximum daily stream temperatures after forest harvesting in several small, nonfish-bearing, headwater streams. Despite these increases, we found no evidence for downstream warming related to upstream harvesting activity.

Rather, heated water from harvested sites rapidly decreased in temperature after flowing into stream reaches with full forest cover. Some of the variability in maximum daily stream temperature response was dependent on the percent of catchment harvested and the catchment lithology. There was no evidence for increases in stream temperature in catchments with a high percent of catchment area harvested, but underlain by permeable geology. This may be due to the buffering effect of increases in summer low flows and greater groundwater or hyporheic exchange. Harvested catchments underlain by resistant (less friable) geology experienced the greatest increases in stream temperature. We believe that this is also an expression of variability in rock permeability and the relative contribution of cooler groundwater during the summer months, which warrants additional research focus.

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## REFERENCES

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *AC-19*, 716–723. https://doi.org/10.1109/TAC.1974.1100705.

Bear, E. A., McMahon, T. E., & Zale, A. V. (2007). Comparative thermal requirements of westslope cutthroat trout and rainbow trout: Implications for species interactions and development of thermal protection standards. *Transactions of the American Fisheries Society*, *136*, 1113–1121. https://doi.org/10.1577/t06-072.1.

Beitinger, T. L., Bennett, W. A., & McCauley, R. W. (2000). Temperature tolerances of North American freshwater fishes exposed to dynamic changes in temperature. *Environmental Biology of Fishes*, *58*, 237–275. https://doi.org/10.1023/a:1007676325825.

Berger, A. M., & Gresswell, R. E. (2009). Factors influencing coastal cutthroat trout (*Oncorhynchus clarkii clarkii*) seasonal survival rates: A spatially continuous approach within stream networks. *Canadian Journal of Fisheries and Aquatic Sciences*, *66*, 613–632. https://doi.org/10.1139/f09-029.

Beschta, R. L., & Taylor, R. L. (1988). Stream temperature increases and land-use in a forested Oregon watershed. *Water Resources Bulletin*, *24*, 19–25. https://doi.org/10.1111/j.1752-1688.1988.tb00875.x.

Beschta, R. L., Bilby, R. E., Brown, G. W., Holtby, L. B., & Hofstra, T. D. (1987). Stream temperature and aquatic habitat: Fisheries and forestry interactions. In E. O. Salo, & T. W. Cundy (Eds.), *Streamside management: Forestry and fishery interactions* (pp. 191–232). Seattle, WA: Institute of Forest Resources, University of Washington.

Bladon, K. D., Cook, N. A., Light, J. T., & Segura, C. (2016). A catchment-scale assessment of stream temperature response to contemporary forest harvesting in the Oregon Coast Range. *Forest Ecology & Management*, *379*, 153–164. https://doi.org/10.1016/j.foreco.2016.08.021.

Bolker, B. M. (2008). *Ecological models and data in R*. Princeton, NJ: Princeton University Press.

Broadmeadow, S. B., Jones, J. G., Langford, T. E. L., Shaw, P. J., & Nisbet, T. R. (2011). The influence of riparian shade on lowland stream water temperatures in southern England and their viability for brown trout. *River Research and Applications*, *27*, 226–237. https://doi.org/10.1002/rra.1354.

Brown, G. W. (1969). Predicting temperatures of small streams. *Water Resources Research*, *5*, 68 -&. doi: https://doi.org/10.1029/WR005i001p00068.

Brown, G. W., & Krygier, J. T. (1970). Effects of clear-cutting on stream temperature. *Water Resources Research*, *6*, 1133–1139. https://doi.org/10.1029/WR006i004p01133.

Bywater-Reyes, S., Segura, C., & Bladon, K. D. (2017). Geology and geomorphology control suspended sediment yield and modulate increases following timber harvest in Oregon headwater streams. *Journal of Hydrology*, *548*, 754–769. https://doi.org/10.1016/j.jhydrol.2017.03.048.

Caissie, D. (2006). The thermal regime of rivers: A review. *Freshwater Biology*, *51*, 1389–1406. https://doi.org/10.1111/j.1365-2427.2006.01597.x.

Caruso, B. S. (2002). Temporal and spatial patterns of extreme low flows and effects on stream ecosystems in Otago, New Zealand. *Journal of Hydrology*, *257*, 115–133. https://doi.org/10.1016/s0022-1694(01)00546-7.

Clinton, B. D. (2011). Stream water responses to timber harvest: Riparian buffer width effectiveness. *Forest Ecology and Management*, *261*, 979–988. https://doi.org/10.1016/j.foreco.2010.12.012.

Cole, E., & Newton, M. (2013). Influence of streamside buffers on stream temperature response following clear-cut harvesting in western Oregon. *Canadian Journal of Forest Research*, *43*, 993–1005. https://doi.org/10.1139/cjfr-2013-0138.

Constantz, J. (1998). Interaction between stream temperature, streamflow, and groundwater exchanges in alpine streams. *Water Resources Research*, *34*, 1609–1615. https://doi.org/10.1029/98wr00998.

D'Angelo, D. J., Gregory, S. V., Ashkenas, L. R., & Meyer, J. L. (1997). Physical and biological linkages within a stream geomorphic hierarchy: A modeling approach. *Journal of the North American Benthological Society*, *16*, 480–502. https://doi.org/10.2307/1468139.

Davis, L. J., Reiter, M., & Groom, J. D. (2015). Modelling temperature change downstream of forest harvest using Newton's law of cooling. *Hydrological Processes*, *30*, 959–971. https://doi.org/10.1002/hyp.10641.

Demars, B. O. L., Manson, J. R., Olafsson, J. S., Gislason, G. M., Gudmundsdottir, R., Woodward, G., … Friberg, N. (2011). Temperature and the metabolic balance of streams. *Freshwater Biology*, *56*, 1106–1121. https://doi.org/10.1111/j.1365-2427.2010.02554.x.

Dent, L., Vick, D., Abraham, K., Schoenholtz, S., & Johnson, S. (2008). Summer temperature patterns in headwater streams of the Oregon Coast Range. *Journal of the American Water Resources Association*, *44*, 803–813. https://doi.org/10.1111/j.1752-1688.2008.00204.x.

Dunham, J., Rieman, B., & Chandler, G. (2003). Influences of temperature and environmental variables on the distribution of bull trout within streams at the southern margin of its range. *North American Journal of Fisheries Management*, *23*, 894–904. https://doi.org/10.1577/m02-028.

Eaton, J. G., & Scheller, R. M. (1996). Effects of climate warming on fish thermal habitat in streams of the United States. *Limnology and Oceanography*, *41*, 1109–1115. https://doi.org/10.4319/lo.1996.41.5.1109.

Ebersole, J. L., Liss, W. J., & Frissell, C. A. (2003). Cold water patches in warm streams: Physicochemical characteristics and the influence of shading. *Journal of the American Water Resources Association*, *39*, 355–368. https://doi.org/10.1111/j.1752-1688.2003.tb04390.x.

Fullerton, A. H., Torgersen, C. E., Lawler, J. J., Faux, R. N., Steel, E. A., Beechie, T. J., … Leibowitz, S. G. (2015). Rethinking the longitudinal stream temperature paradigm: Region-wide comparison of thermal infrared imagery reveals unexpected complexity of river temperatures. *Hydrological Processes*, *29*, 4719–4737. https://doi.org/10.1002/hyp.10506.

Garner, G., Malcolm, I. A., Sadler, J. P., & Hannah, D. M. (2014). What causes cooling water temperature gradients in a forested stream reach? *Hydrology and Earth System Sciences*, *18*, 5361–5376. https://doi.org/10.5194/hess-18-5361-2014.

Gomi, T., Moore, R. D., & Dhakal, A. S. (2006). Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada. *Water Resources Research*, *42*, W08437. https://doi.org/10.1029/2005WR004162.

Gravelle, J. A., & Link, T. E. (2007). Influence of timber harvesting on headwater peak stream temperatures in a northern Idaho watershed. *Forest Science*, *53*, 189–205.

Gregory, S. V., Swanson, F. J., McKee, W. A., & Cummins, K. W. (1991). An ecosystem perspective of riparian zones. *Bioscience*, *41*, 540–551. https://doi.org/10.2307/1311607.

Groom, J. D., Dent, L., Madsen, L. J., & Fleuret, J. (2011). Response of western Oregon (USA) stream temperatures to contemporary forest management. *Forest Ecology and Management*, *262*, 1618–1629. https://doi.org/10.1016/j.foreco.2011.07.012.

Groom, J. D., Johnson, S. L., Seeds, J. D., & Ice, G. G. (2017). Evaluating links between forest harvest and stream temperature threshold exceedances: The value of spatial and temporal data. *Journal of the American Water Resources Association*. https://doi.org/10.1111/1752-1688.12529.

Guenther, S. M., Gomi, T., & Moore, R. D. (2014). Stream and bed temperature variability in a coastal headwater catchment: Influences of surface-subsurface interactions and partial-retention forest harvesting. *Hydrological Processes*, *28*, 1238–1249. https://doi.org/10.1002/hyp.9673.

Hairston-Strang, A. B., Adams, P. W., & Ice, G. G. (2008). The Oregon Forest Practices Act and forest research. In J. Stednick (Ed.), *Hydrological and biological responses to Forest practices* (pp. 95–113). New York, NY: Springer.

Hale, V. C., & McDonnell, J. J. (2016). Effect of bedrock permeability on stream base flow mean transit time scaling relations: 1. A multiscale catchment intercomparison. *Water Resources Research*, *52*, 1358–1374. https://doi.org/10.1002/2014WR016124.

Hall, J. D. (2008). Salmonid populations and habitat. In J. Stednick (Ed.), *Hydrological and biological responses to Forest practices* (pp. 67–93). New York, NY: Springer.

Hawkins, C. P., Hogue, J. N., Decker, L. M., & Feminella, J. W. (1997). Channel morphology, water temperature, and assemblage structure of stream insects. *Journal of the North American Benthological Society*, *16*, 728–749. https://doi.org/10.2307/1468167.

Hester, E. T., & Doyle, M. W. (2011). Human impacts to river temperature and their effects on biological processes: A quantitative synthesis. *Journal of the American Water Resources Association*, *47*, 571–587. https://doi.org/10.1111/j.1752-1688.2011.00525.x.

Hogg, I. D., & Williams, D. D. (1996). Response of stream invertebrates to a global-warming thermal regime: An ecosystem-level manipulation. *Ecology*, *77*, 395–407. https://doi.org/10.2307/2265617.

Ice, G. G. (2008). Stream temperature and dissolved oxygen. In J. Stednick (Ed.), *Hydrological and biological responses to forest practices: The Alsea Watershed Study* (pp. 37–54). New York, NY: Springer Science +Business Media, LLC.

Janisch, J. E., Wondzell, S. M., & Ehinger, W. J. (2012). Headwater stream temperature: Interpreting response after logging, with and without riparian buffers, Washington, USA. *Forest Ecology and Management*, *270*, 302–313. https://doi.org/10.1016/j.foreco.2011.12.035.

Johnson, S. L. (2004). Factors influencing stream temperatures in small streams: Substrate effects and a shading experiment. *Canadian Journal of Fisheries and Aquatic Sciences*, *61*, 913–923. https://doi.org/10.1139/f04-040.

Keith, R. M., Bjornn, T. C., Meehan, W. R., Hetrick, N. J., & Brusven, M. A. (1998). Response of juvenile salmonids to riparian and instream cover modifications in small streams flowing through second-growth forests of southeast Alaska. *Transactions of the American Fisheries Society*, *127*, 889–907. https://doi.org/10.1577/1548-8659(1998)1270889:rojstr2.0.co;2

Kibler, K. M., Skaugset, A., Ganio, L. M., & Huso, M. M. (2013). Effect of contemporary forest harvesting practices on headwater stream temperatures: Initial response of the Hinkle Creek catchment, Pacific northwest, USA. *Forest Ecology and Management*, *310*, 680–691. https://doi.org/10.1016/j.foreco.2013.09.009.

Leach, J. A., & Moore, R. D. (2011). Stream temperature dynamics in two hydrogeomorphically distinct reaches. *Hydrological Processes*, *25*, 679–690. https://doi.org/10.1002/hyp.7854.

Lee, P., Smyth, C., & Boutin, S. (2004). Quantitative review of riparian buffer width guidelines from Canada and the United States. *Journal of Environmental Management*, *70*, 165–180. https://doi.org/10.1016/j.jenvman.2003.11.009.

Levno, A., & Rothacher, J. (1967). Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. USDA Forest Service, PNW Forest and Range Experiment Station, pp: 11.

Luce, C., Staab, B., Kramer, M., Wenger, S., Isaak, D., & McConnell, C. (2014). Sensitivity of summer stream temperatures to climate variability in the Pacific northwest. *Water Resources Research*, *50*, 3428–3443. https://doi.org/10.1002/2013WR014329.

Macdonald, J. S., MacIsaac, E. A., & Herunter, H. E. (2003). The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. *Canadian Journal of Forest Research*, *33*, 1371–1382.

Madej, M. A., Currens, C., Ozaki, V., Yee, J., & Anderson, D. G. (2006). Assessing possible thermal rearing restrictions for juvenile coho salmon (*Oncorhynchus kisutch*) through thermal infrared imaging and in-stream monitoring, Redwood Creek, California. *Canadian Journal of Fisheries and Aquatic Sciences*, *63*, 1384–1396. https://doi.org/10.1139/f06-043.

Malcolm, I. A., Hannah, D. M., Donaghy, M. J., Soulsby, C., & Youngson, A. F. (2004). The influence of riparian woodland on the spatial and temporal variability of stream water temperatures in an upland salmon stream. *Hydrology and Earth System Sciences*, *8*, 449–459. https://doi.org/10.5194/hess-8-449-2004.

Mayer, T. D., & Naman, S. W. (2011). Streamflow response to climate as influenced by geology and elevation. *Journal of the American Water Resources Association*, *47*, 724–738. https://doi.org/10.1111/j.1752-1688.2011.00537.x.

McCullough, D. A., Spalding, S., Sturdevant, D., & Hicks, M. (2001). Summary of technical literature examining the physiological effects of temperature on salmonids. U.S. Environmental Protection Agency, region 10.

McGurk, B. J. (1989). Predicting stream temperature after riparian vegetation removal. In D. L. Abell (Ed.), Technical Coordinator (ed.) *Proceedings of the California riparian systems conference: Protection, management, and restoration for the 1990s* (pp. 157–164). Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture.

Mellina, E., Moore, R. D., Hinch, S. G., Macdonald, J. S., & Pearson, G. (2002). Stream temperature responses to clearcut logging in British Columbia: The moderating influences of groundwater and headwater lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*, 1886–1900. https://doi.org/10.1139/f02-158.

Moore, R. D., & Wondzell, S. M. (2005). Physical hydrology and the effects of forest harvesting in the Pacific northwest: A review. *Journal of the American Water Resources Association*, *41*, 763–784. https://doi.org/10.1111/j.1752-1688.2005.tb03770.x.

Moore, R. D., Spittlehouse, D. L., & Story, A. (2005). Riparian microclimate and stream temperature response to forest harvesting: A review.

*Journal of the American Water Resources Association*, *41*, 813–834. https://doi.org/10.1111/j.1752-1688.2005.tb04465.x.

Moore, R. D., Sutherland, P., Gomi, T., & Dhakal, A. (2005). Thermal regime of a headwater stream within a clear-cut, coastal British Columbia, Canada. *Hydrological Processes*, *19*, 2591–2608.

Morin, A., Lamoureux, W., & Busnarda, J. (1999). Empirical models predicting primary productivity from chlorophyll a and water temperature for stream periphyton and lake and ocean phytoplankton. *Journal of the North American Benthological Society*, *18*, 299–307. https://doi.org/10.2307/1468446.

Moring, J. R., & Lantz, R. L. (1974). Immediate effects of logging on the freshwater environment of salmonids. Oregon Wildlife Commission Research Division, pp: 101.

Penaluna, B. E., Dunham, J. B., Railsback, S. F., Arismendi, I., Johnson, S. L., Bilby, R. E., … Skaugset, A. E. (2015). Local variability mediates vulnerability of trout populations to land use and climate change. *PLoS One*, *10*, e0135334. https://doi.org/10.1371/journal.pone.0135334.

Pinheiro, J. C., & Bates, D. M. (2000). *Mixed-effects models in S and S-plus* (1st ed.). New York, NY: Springer-Verlag.

Pollock, M. M., Beechie, T. J., Liermann, M., & Bigley, R. E. (2009). Stream temperature relationships to forest harvest in western Washington. *Journal of the American Water Resources Association*, *45*, 141–156. https://doi.org/10.1111/j.1752-1688.2008.00266.x.

Poole, G. C., & Berman, C. H. (2001). An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. *Environmental Management*, *27*, 787–802. https://doi.org/10.1007/s002670010188.

Pyne, M. I., & Poff, N. L. (2017). Vulnerability of stream community composition and function to projected thermal warming and hydrologic change across ecoregions in the western United States. *Global Change Biology*, *23*, 77–93. https://doi.org/10.1111/gcb.13437.

R Core Team. (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing.

Reiter, M., Bilby, R. E., & Heffner, J. (2015). Stream temperature patterns over 35 years in a managed forest of western Washington. *Journal of the American Water Resources Association*, *51*, 1418–1435. https://doi.org/10.1111/1752-1688.12324.

Rex, J. F., Maloney, D. A., Krauskopf, P. N., Beaudry, P. G., & Beaudry, L. J. (2012). Variable-retention riparian harvesting effects on riparian air and water temperature of sub-boreal headwater streams in British Columbia. *Forest Ecology and Management*, *269*, 259–270. https://doi.org/10.1016/j.foreco.2011.12.023.

Som, N. A., Zègre, N. P., Ganio, L. M., & Skaugset, A. E. (2012). Corrected prediction intervals for change detection in paired watershed studies. *Hydrological Sciences Journal*, *57*, 134–143. https://doi.org/10.1080/02626667.2011.637494.

Story, A., Moore, R. D., & Macdonald, J. S. (2003). Stream temperatures in two shaded reaches below cutblocks and logging roads: Downstream cooling linked to subsurface hydrology. *Canadian Journal of Forest Research*, *33*, 1383–1396. https://doi.org/10.1139/x03-087.

Studinski, J. M., Hartman, K. J., Niles, J. M., & Keyser, P. (2012). The effects of riparian forest disturbance on stream temperature, sedimentation, and morphology. *Hydrobiologia*, *686*, 107–117. https://doi.org/10.1007/s10750-012-1002-7.

Surfleet, C. G., & Skaugset, A. E. (2013). The effect of timber harvest on summer low flows, Hinkle Creek, Oregon. *Western Journal of Applied Forestry*, *28*, 13–21. https://doi.org/10.5849/wjaf.11-038.

Tague, C., & Grant, G. E. (2004). A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River basin, Oregon. *Water Resources Research*, *40*, W04303. https://doi.org/10.1029/2003wr002629.

Torgersen, C. E., Price, D. M., Li, H. W., & McIntosh, B. A. (1999). Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. *Ecological Applications*, *9*, 301–319. https://doi.org/10.2307/2641187.

Torgersen, C. E., Faux, R. N., McIntosh, B. A., Poage, N. J., & Norton, D. J. (2001). Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment*, *76*, 386–398. https://doi.org/10.1016/s0034-4257(01)00186-9.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*, 130–137.

Venables, W. N., & Ripley, B. D. (2002). *Modern applied statistics with S* (Fourth ed.). New York, NY: Springer.

Wagner, M. J., Bladon, K. D., Silins, U., Williams, C. H. S., Martens, A. M., Boon, S., … Anderson, A. (2014). Catchment-scale stream temperature response to land disturbance by wildfire governed by surface-subsurface energy exchange and atmospheric controls. *Journal of Hydrology*, *517*, 328–338. https://doi.org/10.1016/j.jhydrol.2014.05.006.

Waite, I. R., & Carpenter, K. D. (2000). Associations among fish assemblage structure and environmental variables in Willamette Basin streams, Oregon. *Transactions of the American Fisheries Society*, *129*, 754–770 doi: 10.1577/1548-8659(2000)129<0754:aafasa>2.3.co;2.

Zwieniecki, M. A., & Newton, M. (1999). Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon. *Western Journal of Applied Forestry*, *14*, 106–113.

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