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SUMMER TEMPERATURE PATTERNS IN HEADWATER STREAMS OF THE OREGON COAST RANGE[1]

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ABSTRACT: Cool summertime stream temperature is an important component of high quality aquatic habitat in Oregon coastal streams. Within the Oregon Coast Range, small headwater streams make up a majority of the stream network; yet, little information is available on temperature patterns and the longitudinal variability for these streams. In this paper we describe preharvest spatial and temporal patterns in summer stream temperature for small streams of the Oregon Coast Range in forests managed for timber production. We also explore relationships between stream and riparian attributes and observed stream temperature conditions and patterns. Summer stream temperature, channel, and riparian data were collected on 36 headwater streams in 2002, 2003, and 2004. Mean stream temperatures were consistent among summers and generally warmed in a downstream direction. However, longitudinal trends in maximum temperatures were more variable. At the reach scale of 0.5-1.7 km, maximum temperatures increased in 17 streams, decreased in seven streams and did not change in three reaches. At the subreach scale (0.1-1.5 km), maximum temperatures increased in 28 subreaches, decreased in 14, and did not change in 12 subreaches. Models of increasing temperature in a downstream direction may oversimplify fine-scale patterns in small streams. Stream and riparian attributes that correlated with observed temperature patterns included cover, channel substrate, channel gradient, instream wood jam volume, riparian stand density, and geology type. Longitudinal patterns of stream temperature are an important consideration for background characterization of water quality. Studies attempting to evaluate stream temperature response to timber harvest or other modifications should quantify variability in longitudinal patterns of stream temperature prior to logging.

(KEY TERMS: stream temperature; water quality; shade; cover; riparian forest; rivers/streams; headwater streams.)

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INTRODUCTION

Small headwaters streams make up the majority of the stream network, generate most of the streamflow (MacDonald and Coe, 2007), and provide unique habitats for biological assemblages (Richardson and Danehy, 2007). These small streams contribute to valuable habitat for multiple salmonid species in coastal Oregon watersheds. Population viability for

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many of these species is in question (Nelson *et al.*, 1991). Among other habitat needs, these fish require cool stream temperatures in the summer. Increases in stream temperature at certain life stages can cause stress and/or mortality (Beschta *et al.*, 1987).

It is generally accepted that stream temperature tends to increase in a downstream direction. The rates of change and relationships between basin size and stream temperature patterns have been noted for larger streams and are predicted to increase in a downstream direction (Lewis *et al.*, 1999; Caissie, 2006). However, some studies have observed considerable variability in longitudinal stream temperature patterns, in larger rivers (Torgerson *et al.*, 1999), smaller streams (Johnson, 2004), or side channels (Ebersole *et al.*, 2003). For smaller streams, longitudinal patterns could be highly variable in response to a variety of instream, microclimatic, and geologic processes (Poole and Berman, 2001).

Stream temperature is a function of multiple energy transfer processes including direct solar radiation, longwave radiation, conduction, convection, and evaporation. Of these factors, direct solar radiation is the primary contributor to daily maximum summer stream temperature (Brown and Krygier, 1970; Sinokrot and Stefan, 1993; Johnson, 2004). Therefore, maintaining shade is an effective tool for reducing stream temperature heat flux (Johnson, 2004) during the summer months when maximum stream temperatures are observed.

Riparian forests provide a wide range of structures and functions including but not limited to diverse vegetation types and layered stand structure, snags, downed wood, large wood recruitment to streams, bank stability, nutrient cycling, and shade. Historical forest management that did not require retaining trees along streams resulted in significant reductions in shade and associated increases in stream temperature (Levno and Rothacher, 1967; Brown and Krygier, 1970; Murray *et al.*, 2000). Presently, retention of riparian trees is required along all fish-bearing streams in Oregon during timber harvest (OFPA, 2004) to maintain shade over streams as well as other riparian functions that maintain and protect aquatic habitat. Riparian restrictions around small streams have the potential to be especially costly (Adams *et al.*, 2002). It is important to evaluate stream temperature responses to forest management practices, given the importance of timber harvest to the Oregon economy, the significance of this region to salmonid conservation, and the prevalence of small streams in landscapes.

Geology and channel substrate also have important influences on spatial and temporal stream temperature trends in small streams (Poole and Berman, 2001). Johnson (2004) found that bedrock reaches had wide daily summer stream temperate fluctuations with relatively high maximum and low minimum temperatures. Stream reaches with gravel bottoms and subsurface flows had a much narrower range of daily fluctuations with lower maximums and higher minimums. Ground-water upwellings have potentially greater impacts in headwaters than in downstream reaches (Adams and Sullivan, 1989). Other factors that have been shown to correlate with stream temperature include stream depth (Adams and Sullivan, 1989) and streamflow (Beschta and Taylor, 1988).

In this paper, we describe preharvest spatial and temporal patterns in summer stream temperature for small streams in managed forests in the Oregon Coast Range. We also explore potential sources of variability in summer stream temperature conditions and patterns. The results presented herein are part of a long-term study designed to evaluate effects of forest management on temperature patterns of small streams.

METHODS

Study Area

Stream temperature was studied in 2002, 2003, and 2004 on 36 streams in the Oregon Coast Range. This region is characterized by steep slopes, highly dissected terrain, and sharp ridges with elevations that range from 450 to 750 m for main ridges with a maximum of 1,249 m at Marys Peak. Geology types of the Oregon Coast Range are predominantly layered sandstones and mudstones formed from uplifted ocean sediments that were deposited 60 to 40 million years ago. There are also many basalt intrusions in the north such as those in the vicinity of the Tillamook, Alsea, and Columbia River basins. The study area is influenced by maritime northwest climate patterns with cool, wet winters and mild, dry summers. Maximum air temperatures during study years were 19.0°C, 19.5°C, and 19.9°C from July to September 2002, 2003, and 2004, respectively (OCS, 2006). Rainfall was highly variable in all years and ranged from 2 to 60 mm, 2 to 20 mm, and 1 to 27 mm from July to September in 2002, 2003, and 2004, respectively.

Stream reaches selected for this study are in areas with harvest-regenerated or fire-regenerated forests between 50 and 70 years old (Figure 1). The stream reaches are on managed State of Oregon forests or privately owned industrial forests. In general, Oregon coastal riparian areas are hardwood-dominated, conifer-dominated, or conifer-hardwood mixed and

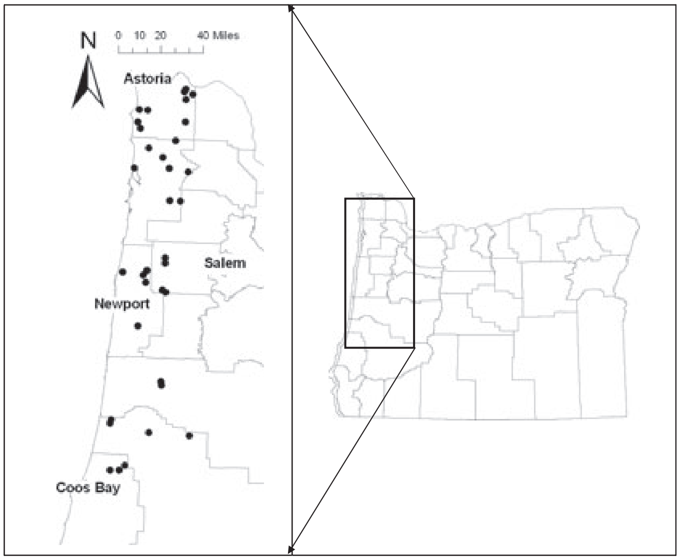

FIGURE 1. Locations of 36 Headwaters Stream Reaches in the Oregon Coast Range.

typically include shrub-dominated openings (Spies *et al.*, 2002). The most common conifer species for this study area is Douglas-fir (*Pseudotsuga menzeisii*) and the most common hardwood species is red alder (*Alnus rubra*). In general, conifer densities increase with increasing distance from stream, whereas hardwoods have not shown clear trends with distance from stream (Pabst and Spies, 1999; Spies *et al.*, 2002). Species composition and structure of riparian vegetation can be influenced by the same disturbances associated with upland stands such as fire, insect and disease, and windthrow. In addition, floods and debris flows have strong influences on riparian characteristics in this region. In general, riparian stands along high-gradient, headwater streams tend to be dominated by conifers. Exceptions include areas disturbed by landslides and debris torrents where red alder, salmonberry (*Rubus spectabilis*), and other deciduous vegetation are dominant (Pabst and Spies, 1999).

Study Design

Stream temperature, channel, and riparian data were collected on 36 stream reaches (defined as the entire length of stream being studied, encompassing two subreaches) as part of a long-term study that utilizes a before-after-control-impact (BACI) approach to examine harvest effects on stream temperature and riparian structure. The design targeted fish-bearing headwater streams classified as small or medium in the Oregon Forest Practices Act (OFPA, 2004). This paper focuses on the pretreatment period: 2002, 2003, and 2004. Because stream reaches were added and the timing of harvest varied, the preharvest sample sizes are 21, 36, and 19, for 2002, 2003, and 2004, respectively.

Because of BACI-related design constraints, a random sample was not practical. We asked all industrial private and state forest managers in the Oregon Coast Range to provide a list of stream reaches that would be harvested within a specific time frame and also met other criteria or constraints (Table 1). An initial list of 130 stream reaches was reduced to the final 36 and includes all stream reaches that met design constraints. Disturbances from beaver activities and debris-torrents, although common in the Oregon Coast Range, were avoided because such disturbances can overwhelm temperature patterns that otherwise could be influenced by harvesting in the posttreatment stage of this project. The final set of stream reaches, while not a random sample, is likely to represent conditions in 50-70-year-old forests, primarily managed for timber production, with small streams that lack recent debris torrent or beaver disturbance, on state and industrial private forest ownership in the Oregon Coast Range.

The majority (77%) of coastal forests in Oregon is under private (68%) or state (9%) ownership and managed for timber production (Spies *et al.*, 2002). Findings from this study are most applicable to streams in mid-successional forests (50-70-year-old conifer), which also make up the majority (82%) of Oregon state and private forests (Spies *et al.*, 2002). These sites do not represent, nor are they intended to represent unmanaged, old growth, or late-successional forest conditions and associated stream temperature patterns. Given that only 5-11% of the Oregon Coast Range is currently estimated to be in old growth or late-successional forest (Wimberly *et al.*, 2000), this study of stream reaches in mid-successional forests has relevance to regional conditions.

TABLE 1. Criteria Used to Select Stream Reaches for Evaluation of Summer Temperature Patterns of Headwater Streams in the Oregon Coast Range.

Site Selection Criteria
Ability to collect at least two years of pretreatment and seven years of posttreatment data
Fish-bearing streams
Minimum subreach lengths of 300 m
Streams must have an upstream "control" subreach that remains unharvested for duration of study
Estimated mean annual streamflow < 280 l/s
No major changes in channel and valley morphology, streamflow, or riparian attributes within streams reaches
No recent impacts from debris torrents
No active beaver ponds and ideally no large abandoned beaver ponds

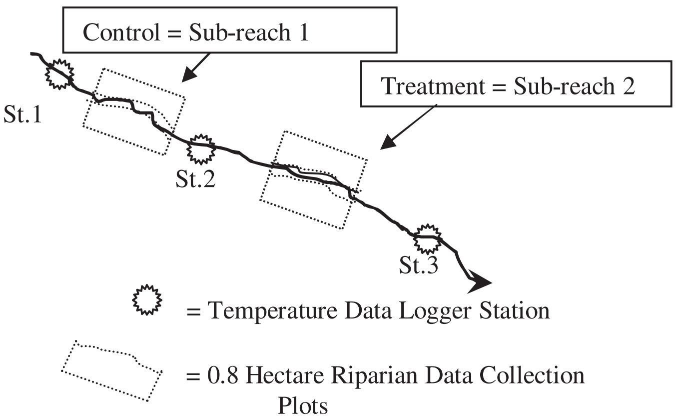

FIGURE 2. Schematic of Stream Reach (full length of stream being studied between Stations 1 and 3) Layout, Probe, and Riparian Plot Locations for 36 Headwater Streams in the Oregon Coast Range. "Subreach 1" (stream length between Stations 1 and 2) will remain as the control reach. "Subreach 2" (stream length between Stations 2 and 3) will become the treatment reach for the longer term study evaluating effects of harvesting on stream temperature. Canopy and channel data were collected at 60-m intervals in both subreaches.

Stream reach lengths varied from 525 to 1,768 m, with a mean of 932 m. Two subreaches (defined as a subsection of the study reach) were established on each stream reach (Figure 2). Subreach 1 will remain unharvested for the life of the study and serves as the "control" reach. Subreach 2, is immediately downstream of Subreach 1 and will eventually serve as the "treatment" reach after harvest. While the goal of the design was to have subreach lengths of ≥300 m, final subreach lengths varied from 137 to 1,494 m with a mean of 466 m. Factors which dictated final subreach lengths included future harvest unit boundaries in Subreach 2, large changes in valley or channel characteristics, or tributary inputs and junctions.

Stream Temperature and Flow Measures

Summer stream temperatures were recorded hourly between June and September 2002, 2003, and 2004 with continuously recording temperature data loggers (Optic Stowaway and Water Temp Pro, Onset Computer Corporation, Bourne, Massachusetts) at three stations in each reach. Predeployment and postdeployment accuracy checks were conducted using cold-water submersion and an NIST thermometer (Dunham *et al.*, 2005). Temperature stations were established at upstream and downstream boundaries of Subreaches 1 and 2 (Figure 2). Station locations were based on boundaries of future harvest units such that Station 1 would be approximately 300 m upstream of the future harvest unit, Station 2 at the upstream end of the harvest unit boundary, and Station 3 at the downstream end of the harvest unit boundary. Streamflow was calculated from measurements of velocity and cross-sectional areas at Station 3 in June, July, August, or September.

Channel Attributes

The following data were collected at measurement stations spaced 60 m apart throughout each subreach, following methods described in Lazorchak *et al.* (1998). Forest and shrub canopy cover was measured with a hand-held densiometer in each of four directions (upstream, left, right, and downstream) in the middle of the channel. Hemispherical photography was used to measure shade. A camera, with a "fish-eye" lens, was leveled at 1 m above the water surface and oriented to the north. Fish-eye photos were processed into electronic format and analyzed with Hemiview Software™ to calculate the amount of solar energy intercepted by canopy cover. Wetted width (wetted surface) and bankfull width (at the estimated average annual high water mark) were measured using a surveyor's rod or tape measure. Flood-prone width is the length measured at the elevation of two-times the bankfull height between flow-confining topographic features (Rosgen, 1994). It was measured using a surveyor's rod or tape measure. Channel gradient was measured using a clinometer. Substrate was characterized with a visual estimate of the percent of channel bed composed of each of six size classes of material (bedrock, boulder, cobble, gravel, sand, or fines). All instream wood jams in both subreaches were measured. A wood jam was defined as numerous pieces of wood functioning as a unit and piled together such that an individual wood tally was inaccurate. The length (L), width (W), and height (H) of each wood jam was measured and multiplied ($L \times W \times H$) to provide an estimate of wood jam volume.

Riparian-Structure Attributes

Riparian attributes were measured in permanent rectangular plots (0.8 ha), 152 m long (parallel to stream) by 52 m wide (horizontal distance from stream) centered within each subreach, one on each side of the stream, for a total of four plots per stream reach (Figure 2). The plot width was based on riparian buffers widths (52 m) that will be used when sites are harvested. Plot length was chosen to represent heterogeneous riparian forest conditions in a cost-effective manner. In heterogeneous forests, large plots or multiple small plots are needed to accurately describe stand structure (Husch *et al.*,1972). We opted for fewer large plots to control costs associated with establishing the plot itself. The species and distance from stream were recorded for every tree with a diameter at breast height (DBH) ≥14 cm.

Analytical Methods

Stream Temperature Metrics. The daily mean, maximum, and minimum stream temperature for each station were derived from hourly data recorded between July 15th and August 30th in 2002, 2003, and 2004. Diurnal fluctuation and maximum seven-day moving mean of the daily maximum (7DAYMAX) were calculated from the daily statistics. Diurnal fluctuation is the daily maximum minus the daily minimum. The 7DAYMAX is used by the Oregon Department of Environmental Quality (ODEQ) as a metric for evaluating if streams meet Oregon water quality standards for temperature (ODEQ, 2006). The 7DAYMAX is calculated using a running average of daily maximum stream temperatures for a seven-day period, then repeating the calculation after dropping the first day and adding the eighth day of record. This is repeated for the entire period of record for each station yielding a seven-day moving mean of daily maximum for each day, the warmest of which is the 7DAYMAX for the season. We identified the 7DAYMAX for each season at Station 3 for each stream reach. The date when the 7DAYMAX occurred at Station 3 was then used to select the corresponding temperature metrics for Stations 1 and 2 to be used for within-reach comparisons.

The ODEQ establishes two numeric standards for fish bearing headwater streams in the Oregon Coast Range (ODEQ, 2006). Streams that provide salmonid spawning habitat are expected to have 7DAYMAXs ≤ 16°C, whereas streams that provide salmonid migration habitat must have 7DAYMAXs ≤ 18°C. We calculated 7DAYMAX between July 15th and August 30th, in 2002, 2003, and 2004 and evaluated it against the appropriate DEQ standard.

Longitudinal Patterns. Streams were designated as having a "warming" pattern if the 7DAYMAX was warmer at the downstream Station 3 relative to the upstream Station 1 or a "cooling" pattern if the 7DAYMAX was cooler at the downstream Station 3 relative to the upstream Station 1. A "no-change" designation was defined as ±0.2°C between Stations 1 and 3, which reflects the factory-established accuracy of temperature probes used for this research.

To account for differences in subreach lengths, we calculated a normalized rate of change in 7DAYMAX per 300 m. Differences between 7DAYMAX at the downstream and upstream stations were divided by the distance between stations and multiplied by 300 m (change in °C/300 m).

Statistical Analyses. We used SAS Version 9.1 (SAS Institute Inc., Cary, North Carolina) for all statistical analyses. Stream temperatures at each sampling location are influenced by upstream channel- and riparian-zone attributes. Therefore, a paired *t*-test for dependent samples was used to evaluate differences in mean channel and riparian attributes between Subreaches 1 and 2. A paired *t*-test for dependent samples was also used to evaluate differences in average of the daily mean, minimum, maximum, and 7DAYMAX stream temperatures between stations. A Pearson correlation analysis was conducted to examine potential sources of observed variability in stream temperature. This analysis was performed on data from 2003 because that year had the greatest sample size and most complete record of stream temperatures.

RESULTS

Stream Channel and Riparian Characteristics

Twenty-three stream reaches were in sedimentary and 13 were in igneous geologic types. Stream reaches were steep, shallow, narrow, confined, and well shaded, with substrates composed primarily of fines and gravel (Table 2). Stream channel attributes were consistent between subreaches with the exception of gradient ($p = 0.02$), wetted width ($p = 0.001$), and bankfull width ($p = 0.0002$). The upstream subreaches had higher mean gradients, narrower wetted widths, and narrower bankfull widths than the downstream subreaches (Table 2). The stream reaches had low streamflows that varied from a low of 1 l/s to a high of 38 l/s, with a mean of 9 l/s.

Mean conifer basal area increased with distance from stream. The near-stream zones (within 8 m of stream) were dominated by a hardwood overstory stand type with a mean hardwood basal area of 28 m^2/ha as compared with a mean conifer basal area of 14 m^2/ha (Table 3). Conifers were more common beginning at 9-15 m zone from the stream. At 31-52 m from the stream, conifer basal area (36 m^2/ha) was four times that of hardwoods (9 m^2/ha).

TABLE 2. Mean and Standard Deviation of Channel and Riparian Attributes for Subreaches 1 and 2 for 36 Streams in the Oregon Coast Range.

Attribute	Mean (standard deviation)	
	Subreach 1	Subreach 2
Streamflow (l/s)	NA	9.1 (7.7)
Channel gradient (%)*	9.6 (8.9)	6.5 (4.2)
Fines (%)	38 (23)	34 (21)
Gravel (%)	38 (17)	38 (13)
Cobble (%)	18 (13)	19 (12)
Boulder (%)	3 (5)	4 (7)
Bedrock (%)	4 (12)	6 (11)
Thalwag depth (m)	0.2 (0.1)	0.2 (0.1)
Wetted width (m)*	1.7 (0.7)	2.1 (0.8)
Bankfull width (m)*	3.5 (1.1)	4.3 (1.4)
Flood prone width (m)	10.1 (8.8)	12.3 (7.0)
Distance from divide (m)	1551 (805)	2203 (867)
Shade (%)	86 (7)	87 (6)
Cover (%)	93 (4)	93 (4)
Wood jam index (m^3/m)	2 (14)	1(8)
Basal area (m^2/ha)	43 (14)	45 (13)
Trees/ha	870 (252)	914 (301)
Sedimentary geology type	23 sites	
Igneous geologic type	13 sites	

Note: For a given attribute, statistical difference (α = 0.05) between Subreaches 1 and 2 is indicated with *.

Range of Observed Stream Temperature Conditions

Stream temperatures among individual reaches in this study were highly variable. During the three summers, daily maximum ranged from 7.3°C to 20.4°C, daily minimum from 6.7°C to 16.2°C, and daily mean from 7.0°C to 17.0°C. Daily diurnal fluctuation in summer varied from 0°C to 9.3°C (Figures 3A, 3B, and 3C). The rate of change in 7DAYMAX/300 m varied from −1.6°C/300 m to +3.6°C/300 m (Figure 4). There were no significant differences in mean rate of change among reaches. When we compared rate of change in 2002 to rate of change in 2003 for only those streams sampled in both years, there was no statistical difference between years.

We observed a narrow range of mean temperature conditions. Mean maximum temperatures observed at all stations over the three-year period varied from 12.2°C to 13.9°C, mean minimums from 11.3°C to 12.7°C, overall mean values varied from 11.7°C to 13.2°C, and mean diurnal fluctuation varied from 0.9°C to 1.3°C. The mean 7DAYMAX ranged from 12.2°C to 13.8°C (Table 4). Thirty percent (5/16) and 10% (2/20) of the stream reaches exceeded the ODEQ 7DAYMAX water quality standard at least one day during one of the summers for the 16°C and 18°C standards, respectively.

TABLE 3. Mean Conifer and Hardwood Basal Area in Riparian Zones With Increasing Distance From Streams (n = 36).

Distance From Stream (m)	Conifer Basal Area (m^2/ha)	Hardwood Basal Area (m^2/ha)
0-8	14	28
9-15	25	13
16-23	29	12
24-30	34	10
31-52	36	9

Note: Plots along both subreaches were averaged for this summary.

Longitudinal Patterns

Statistically significant differences in mean values between Stations 1 and 2 and 1 and 3 were observed in all three years (Table 5). Differences between Stations 2 and 3 were only significant in 2003. The results were consistent in that all statistically significant changes represent an increase in temperature in a downstream direction. However, changes were not observed for all temperature metrics, for all reaches, or for all years.

Longitudinal patterns in 7DAYMAX stream temperatures were more variable at both the reach and subreach scales. This analysis was performed on 27 streams because of missing data on nine streams. Longitudinal stream temperature patterns were variable between subreaches and among streams in 2003. Of 27 streams, some displayed a warming pattern in both subreaches, a cooling pattern in both subreaches (Figures 5 and 6), no-change in both subreaches, or some combination of the three. Overall, 63% of the streams warmed, 26% cooled, and 11% had no-change at the stream reach scale with variable patterns at the subreach scale (Table 6).

Sources of Variability

Correlations between 7DAYMAX temperature and stream attributes showed significant positive correlations for bedrock and negative correlations for fines for Subreach 1. In Subreach 2, gradient, wood jam volume, and riparian stand density were negatively correlated with 7DAYMAX, while sedimentary geology was positively correlated. No attributes were significantly correlated with 7DAYMAX in both subreaches (Table 7).

The rate of change in 7DAYMAX/300 m was positively correlated with mean bedrock in Subreach 1 and negatively correlated with cover. In Subreach 2, however, rate of change in 7DAYMAX/300 m was negatively correlated with mean bedrock and positively correlated with percent fines (Table 7).

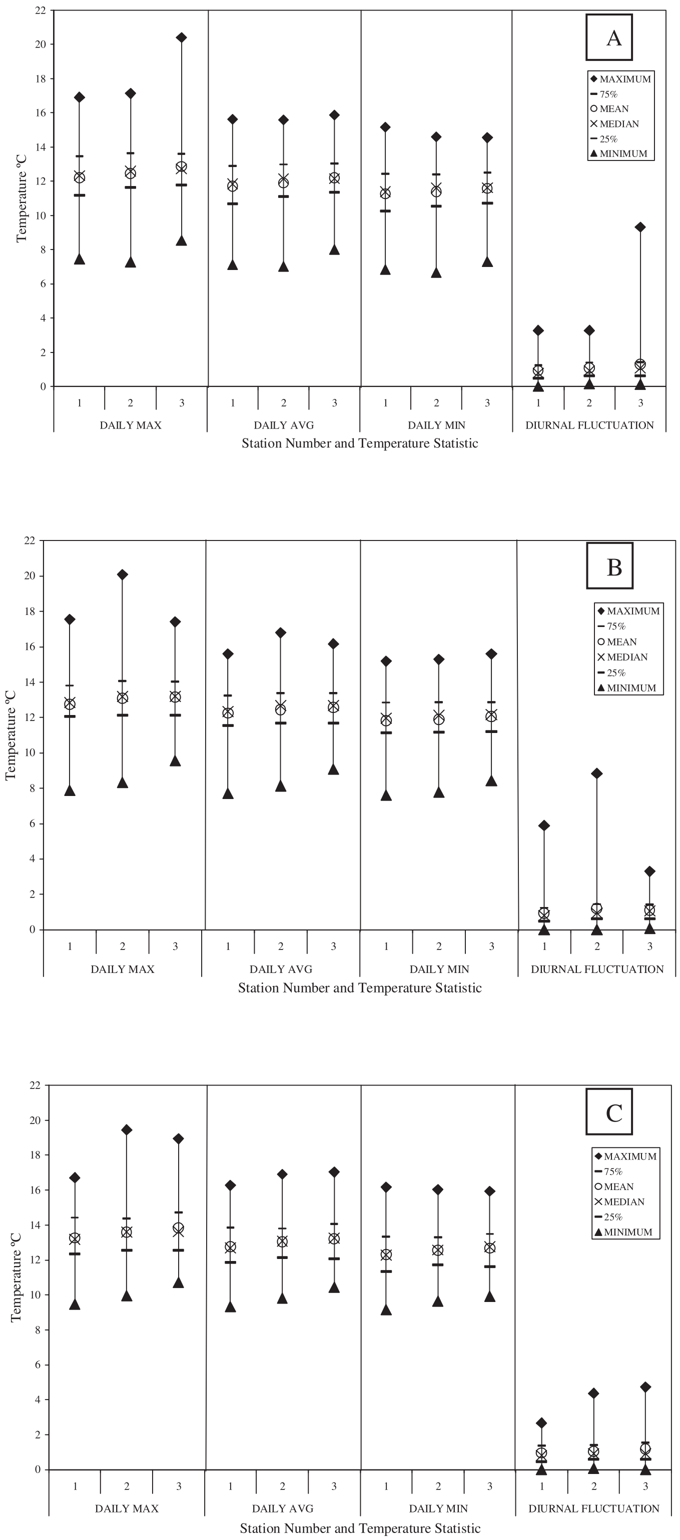

FIGURE 3. Stream Temperature Statistics for (A) 2002, (B) 2003, and (C) 2004 at Stations 1, 2, and 3 (n = 21, 36, and 19 for 2002, 2003, and 2004, respectively) for Headwater Streams in the Oregon Coast Range. Daily statistics were calculated from hourly data collected from 7/15 to 8/30 each year. Observed daily minimums, maximums, 75th and 25th quartiles, mean and medians of the distributions are shown.

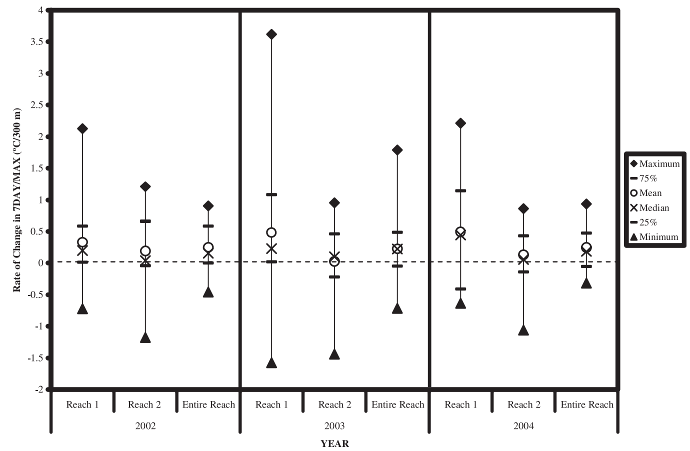

FIGURE 4. Rate of Change in 7DAYMAX/300 m for Subreach 1, Subreach 2, and the Entire Reach for 2002, 2003, and 2004 (n = 21, 36, and 19, respectively) for Headwater Streams in the Oregon Coast Range. The 7DAYMAX and associated rate of change were calculated using daily statistics from hourly data collected from 7/15 to 8/30 each year. The observed daily minimums, maximums, 75th and 25th quartiles, mean and medians of the distributions are shown.

DISCUSSION

We observed a high degree of variability in summertime stream temperature conditions and patterns in these headwater streams. Most notable from this set of streams was the observed variability in longitudinal patterns at small subreach scales. In general mean stream temperature increased in a downstream direction. However, longitudinal patterns for 7DAYMAX temperatures were more complex displaying alternating warming and cooling trends at subreach scales. These findings suggest that a simple model of increasing temperature in a downstream direction does not adequately characterize temperature patterns for many of these small streams. Observed reach-to-reach variability was likely a result of spatially variable instream processes that influence temperature patterns at small reach scales (0.5-2 km in length).

Similar variability in stream temperature patterns is cited by Poole and Berman (2001). Torgerson *et al.* (1999) and Ebersole *et al.* (2003) also found heterogeneous longitudinal patterns of summer stream temperature in northeastern Oregon. In contrast, Brown (1970), Zwieniecki and Newton (1999), and Lewis *et al.* (1999) found predictable patterns of warming in a downstream direction under full canopy cover. While not quantified in this study, possible explanations for observed longitudinal patterns include entrance of cool tributaries and influx of ground water (Beschta *et al.*, 1987; Ebersole *et al.*, 2003). Hewlett and Fortson (1982) determined ground-water input to be

TABLE 4. Mean Values of Temperatures Calculated From Hourly Data Collected From July 15 to August 30.

Year	Station (*n*)	Daily Maximum (°C)	Daily Minimum (°C)	Daily Mean (°C)	Diurnal Fluctuation (°C)	7-Day Maximum (°C)
2002	1 (19)	12.2	11.3	11.7	0.9	12.2
	2 (20)	12.5	11.4	11.9	1.1	12.5
	3 (21)	12.9	11.6	12.2	1.3	12.9
2003	1 (31)	12.8	11.8	12.2	0.9	12.8
	2 (30)	13.1	11.9	12.5	1.2	13.1
	3 (36)	13.2	12.0	12.6	1.1	13.1
2004	1 (19)	13.3	12.3	12.8	1.0	13.3
	2 (18)	13.6	12.6	13.0	1.0	13.6
	3 (19)	13.9	12.7	13.2	1.2	13.8

TABLE 5. Paired *t*-Test Results (for dependent samples) Comparing Mean Stream Temperature Metrics Between Stations.

		Difference in Mean Temperature Between Stations		
Temperature Metric	**Stations Being Compared**	**2002 °C (*p*-value)**	**2003 °C (*p*-value)**	**2004 °C (*p*-value)**
Daily max	1 & 2		0.87 (0.02)	0.08 (0.02)
	2 & 3			
	1 & 3	1.02 (0.03)	0.72 (0.01)	0.03 (0.02)
Daily min	1 & 2		0.53 (0.01)	
	2 & 3		0.30 (0.01)	
	1 & 3		0.51 (<0.01)	0.34 (0.04)
Daily average	1 & 2	0.68 (0.03)	0.41 (0.05)	0.16 (0.05)
	2 & 3			
	1 & 3		0.23 (<0.01)	0.50 (0.01)
7DAYMAX	1 & 2	0.29 (0.05)	0.43 (0.03)	0.42 (0.04)
	2 & 3			
	1 & 3	0.90 (0.02)	0.63 (0.01)	0.73 (0.01)

Note: Statistically significant differences in mean values and *p*-values are provided. All observed changes represent increases between stations.

the primary driver of stream temperature in small streams in the southeastern United States Adams and Sullivan (1989) also argued that ground-water contributions play an important role in temperature patterns. Studies attempting to evaluate stream temperature response to timber harvest should consider the variable longitudinal patterns of stream temperature that can exist prior to disturbance as observed in these study sites.

Streams in this study were consistently well-shaded with high levels of canopy cover. Selection criteria for this study that excluded sites with recent human and natural disturbances such as beaver and debris torrents, in part explain consistently high cover conditions. Such conditions limited the usefulness of cover or shade as a predictor of stream temperature variability prior to logging. Other studies (Levno and Rothacher, 1967; Brown and Krygier, 1970; Beschta and Taylor, 1988; Jackson *et al.*, 2001) of canopy cover prior to logging in the Pacific Northwest have reported similar canopy conditions as observed in this study. Solar radiation is a key driver of midday high stream

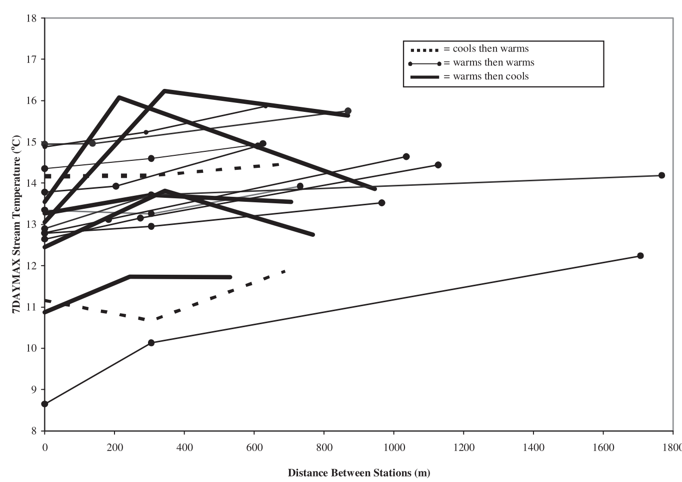

FIGURE 5. 7DAYMAX Temperature *vs.* Distance Between Stations (Station 1 = 0 m) for Streams in the Oregon Coast Range That had an Overall *Warming* Pattern (between Stations 1 and 3) in 2003 (n = 17). Thin solid line represents streams that warmed in both reaches, heavy solid line represents streams that warmed in Subreach 1 but cooled in Subreach 2, and dashed line represents streams that cooled in Subreach 1 but warmed in Subreach 2.

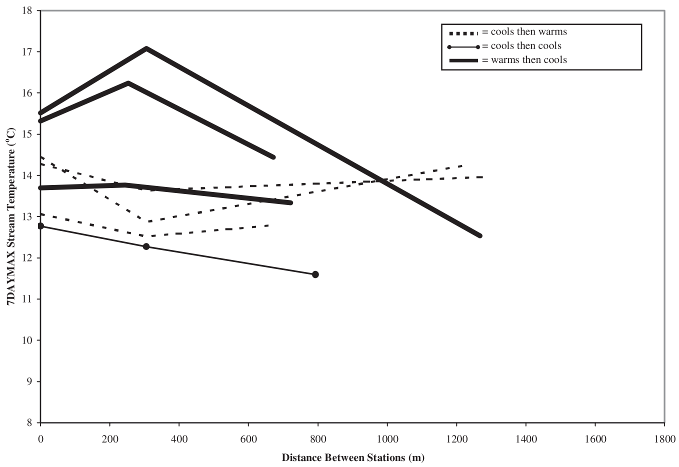

FIGURE 6. 7DAYMAX Temperature *vs.* Distance Between Stations (Station 1 = 0 m) for Streams in the Oregon Coast Range That Had an Overall *Cooling* Pattern (between Stations 1 and 3) in 2003 (n = 7). Thin solid line represents streams that cooled in both reaches, heavy solid line represents streams that warmed in Subreach 1 but cooled in Subreach 2, and dashed line represents streams that cooled in Subreach 1 but warmed in Subreach 2.

temperatures (Beschta and Taylor, 1988; Brown, 1988; Sinokrot and Stefan, 1993) and several studies have established the importance of shade for maintaining stream temperature (Brown, 1970, 1988; Beschta *et al.*, 1987; Lewis *et al.*, 1999; Zwieniecki and Newton, 1999). If future harvest reduces shade, we expect the correlative relationships between shade and stream temperature for these stream reaches to strengthen.

We observed greater extremes in stream temperature and rate of change than reported in other studies (Brown and Krygier, 1970; Amaranthus *et al.*, 1989; Dupuis and Steventon, 1999; Jackson *et al.*, 2001). Higher variability in temperature patterns observed in this study may be a result of our focus on small streams, regional differences, and our larger sample size. Small streams may be more susceptible to temperature variations as a result of low flow volumes and interactions with ground water and substrate. A large sample size may have increased the likelihood of capturing a greater range in conditions.

Channel substrates, specifically the percent fines, percent bedrock, and geologic type were correlated with stream temperature and rate of change with alternating positive and negative relationships by subreach. Johnson (2004) found that streams dominated by bedrock tended to have wide daily summer stream temperate fluctuations with relatively high maximum and low minimum temperatures. Ebersole *et al.* (2003) described cool water in streams as associated with substrate characteristics and localized conditions. Cool temperatures may be responding to conductive heat exchange with the substrate, whereby the slightly warmer stream water is losing heat to the still seasonally cool substrate (Brown, 1988). This hypothesis corresponds to the findings of Sinokrot and Stefan (1993), who found that conduction among shallow, small streams, and the streambed should be considered in heat budget estimates. While similarly variable results have been reported in other research, it is possible that alternating positive and negative correlations between temperature and substrate in this study may reflect over-simplified substrate measures that are inadequate to explain complex cooling and heating processes that result from surface water/channel interactions.

CONCLUSIONS

This study provided several observations with important implications for management and research

TABLE 6. Number and Percent of Streams With Cooling, Warming, or No-Change Patterns in 2003 for 7DAYMAX at the Stream Reach (Stations 1-3) and Subreach Scales for 27 Headwater Streams in the Oregon Coast Range.

Site Level Pattern (percent of sites)	Number of Sites	Subreach 1 Pattern	Subreach 2 Pattern	Percent of Sites With Subreach Pattern
Overall warming pattern	6	Warms	Warms	22
between Stations	5	No change	Warms	19
1 and 3 (63%)	3	Warms	Cools	11
	2	Warms	No change	7
	1	Cools	Warms	4
Overall cooling pattern	3	Cools	Warms	11
between Stations	2	Warms	Cools	7
1 and 3 (26%)	1	No change	Cools	4
	1	Cools	Cools	4
No-change between	2	No change	Cools	7
Stations 1 and 3 (11%)	1	No change	No change	4

Note: No-change was defined as ±0.2°C based on the accuracy of temperature probes.

TABLE 7. Pearson Correlation Results Relating 2003 7DAYMAX at Stations 2 and 3 to Upstream Attributes for Subreaches 1 and 2, Respectively, for Headwater Streams in the Oregon Coast Range.

	7DAYMAX (°C)		Rate of Change (°C/300 m)	
Channel or Riparian Parameter (n = 25 except when shown)	**Subreach 1 r (p-value)**	**Subreach 2 r (p-value)**	**Subreach 1 r (p-value)**	**Subreach 2 r (p-value)**
Distance from divide (30)	0.31 (0.09)	0.32 (0.06)	0.00 (0.99)	0.01 (0.95)
Mean % bedrock	0.49 (0.01)*	−0.14 (0.45)	0.43 (0.05)*	−0.52 (0.01)*
Mean % gravel	−0.07 (0.75)	−0.24 (0.18)	−0.11 (0.61)	−0.11 (0.58)
Mean % cobble	0.14 (0.50)	−0.17 (0.36)	−0.28 (0.21)	−0.07 (0.72)
Mean % boulder	0.31 (0.13)	−0.01 (0.97)	0.22 (0.33)	0.00 (0.98)
Mean %fines	−0.40 (0.05)*	0.31 (0.08)	−0.07 (0.77)	0.40 (0.04)*
Mean wetted width	0.24 (0.25)	0.10 (0.60)	0.04 (0.87)	0.19 (0.35)
Mean bankfull width	0.26 (0.21)	−0.04 (0.84)	0.12 (0.59)	−0.10 (0.65)
Mean flood-prone width	0.11 (0.61)	0.23 (0.21)	−0.07 (0.75)	0.24 (0.24)
Mean max depth	−0.09 (0.68)	0.14 (0.44)	−0.13 (0.58)	0.15 (0.46)
Mean % gradient	−0.25 (0.23)	−0.48 (0.01)*	−0.13 (0.57)	−0.12 (0.56)
Mean % cover	−0.03 (0.90)	0.23 (0.21)	−0.54 (0.01)*	−0.18 (0.39)
Mean % shade (27)	−0.17 (0.38)	0.05 (0.76)	−0.31 (0.14)	−0.07 (0.73)
Wood jam volume (34)	−0.19 (0.33)	−0.38 (0.02)*	−0.17 (0.46)	0.20 (0.29)
Mean basal area/ha (28)	−0.12 (0.53)	−0.01 (0.95)	−0.04 (0.86)	0.25 (0.21)
Mean no. of trees/ha (28)	−0.12 (0.53)	−0.36 (0.04)*	−0.17 (0.42)	0.10 (0.61)
Sedimentary geology	0.18 (0.36)	0.45 (0.01)*	−0.18 (0.37)	0.17 (0.37)

Notes: Rate of change in 7DAYMAX/300 m in Subreaches 1 and 2 was likewise compared with Subreaches 1 and 2, respectively.
*Statistically significant correlation (α = 0.05).

on small streams in similar ecological settings as the Oregon Coast Range. Findings highlight the complexity of processes influencing stream temperature at small reach scales in the stream reaches we studied. We intentionally selected small streams that had similar forest management and disturbance histories and channel characteristics which were reflected in narrow ranges of shade and channel conditions. Nevertheless, we observed a wide range of stream temperature conditions and spatial patterns prior to harvest.

Under current forest management, shade is provided by maintaining riparian buffer zones in part to prevent adverse impacts of harvest operations on stream temperature. This is appropriate as greater canopy cover can be a significant predictor of cooler stream temperatures. However, the inherent complexity in small streams observed in this study indicates that additional processes may determine stream temperature conditions and patterns when shade and canopy cover are consistently high. Given the potential influence of substrate and streamflow on temperature patterns in small streams, future studies should consider precise measures of substrate, streamflow, and/or hyporheic exchange. An examination of ground-water-surface water interactions in small streams may explain if this interaction has a modifying affect on harvest response. Given the observed variability in temperature patterns and correlations between temperature and stream characteristics, postharvest evaluations will need to account for inherent variability observed prior to harvest.

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