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RESEARCH ARTICLE

Spatial and seasonal variability of forested headwater stream temperatures in western Oregon, USA

J. A. Leach[1,2] · D. H. Olson[3] · P. D. Anderson[3] · B. N. I. Eskelson[1]

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Abstract Thermal regimes of forested headwater streams control the growth and distribution of various aquatic organisms. In a western Oregon, USA, case study we examined: (1) forested headwater stream temperature variability in space and time; (2) relationships between stream temperature patterns and weather, above-stream canopy cover, and geomorphic attributes; and (3) the predictive ability of a regional stream temperature model to account for headwater stream temperature heterogeneity. Stream temperature observations were collected at 48 sites within a 128-ha managed forest in western Oregon during 2012 and 2013. Headwater stream temperatures showed the greatest spatial variability during summer (range up to 10 °C) and during cold and dry winter periods (range up to 7.5 °C), but showed less spatial variability during spring, fall and wet winter periods (range between 2 and 5 °C). Distinct thermal regimes among sites were identified; however, geomorphic attributes typically used in regional stream temperature models were not good predictors of thermal variability at headwater scales. A regional stream temperature model captured the mode of mean August temperatures observed across the study area, but overpredicted temperatures for a quarter of the sites by up to 2.8 °C. This study indicates considerable spatial thermal variability may occur at scales not resolved by regional stream temperature models. Recognizing this sub-landscape variability may be important when predicting distributions of aquatic organisms and their habitat under climate and environment change scenarios.

Keywords Stream temperature · Stream networks · Headwater · Pacific Northwest · Aquatic habitat

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✉ J. A. Leach
jason.leach@slu.se

[1] Department of Forest Resources Management, The University of British Columbia, Vancouver, Canada

[2] Present Address: Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Umeå, Sweden

[3] USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, Corvallis, OR, USA

Introduction

Stream temperature exerts a primary control on the spatial distribution of aquatic organisms in stream networks (Rieman et al. 2007; Isaak et al. 2015). Climate and environmental changes, such as forest management, wildfire, and urbanization, are affecting stream thermal regimes (Brown 1969; Pluhowski 1970; Moore et al. 2005b; Isaak et al. 2010; Leach and Moore 2010; Holsinger et al. 2014). Consequently, there are concerns that suitable thermal habitats for temperature sensitive aquatic organisms are being lost or degraded (Wehrly et al. 2003; Durance and Ormerod 2007; Friberg et al. 2013; Parkinson et al. 2015). In order to develop effective management to sustain aquatic ecosystems, we need a better understanding of stream thermal regimes across multiple spatial and temporal scales (Arismendi et al. 2012).

Over the last two decades there have been considerable efforts to understand variability of stream thermal regimes at a range of spatial scales (Webb et al. 2008). A major focus of this research has been empirical studies conducted at regional stream network scales (e.g., Gardner et al. 2003; Wehrly et al. 2009; Daigle et al. 2010; Hrachowitz et al. 2010; Isaak et al. 2010; Chang and Psaris 2013; Imholt et al. 2013; Moore et al. 2013). These studies have consisted of stream temperature measurements typically made across multiple catchments and over distances of tens to thousands of kilometers. Results consistently show that much of the regional variability in stream temperature can be related to air temperature and stream flow, as well as landscape characteristics such as catchment area, elevation, slope, aspect, land cover, and riparian vegetation and topographic shading.

In contrast to the number of regional-scale stream temperature studies, there have been fewer studies that have looked at spatial variability of stream temperature across stream networks at the scale of tens to hundreds of meters. Brown and Hannah (2008) and Cadbury et al. (2008) documented spatial stream temperature heterogeneity of small stream networks in glaciated catchments of the French Pyrénées and New Zealand, respectively. Both studies found that stream temperature variability at this scale was associated with water source (glacier melt or hillslope runoff) and local site characteristics, such as elevation, aspect and stream length. Imholt et al. (2013) monitored stream temperatures at a range of scales (longitudinal variability of the mainstem channel, inter-tributary variability, and lateral and longitudinal variability of a 30 m reach) for a large catchment in Scotland (2100 km^2 catchment area). They found thermal variability at all spatial scales, and suggested that accounting for elevation, catchment size, and forest cover was important at the catchment scale, forest cover was important when comparing tributaries, and hydraulic condition and water source were important at the reach scale.

A number of studies documented longitudinal heterogeneity of stream temperature along headwater stream reaches using measurements distributed at 30–1000 m intervals (e.g., Danehy et al. 2005; Gravelle and Link 2007; Leach and Moore 2011; Garner et al. 2014; Dick et al. 2015), where the degree of spatial heterogeneity documented at the reach scale varied and reflected differences in dominant energy fluxes controlling stream temperatures (e.g., surface energy fluxes and advection associated with groundwater and hyporheic exchange). A few other studies have reported thermal variability over short (<1 m) distances within a stream reach (e.g., Rutherford et al. 1993; Clark et al. 1999; Bormans and Webster 1998; Moore et al. 2005b; Imholt et al. 2013). Overall, these studies highlight that considerable variability in stream temperature may exist at fine spatial scales (<1000 m), which may be important for providing suitable habitat for aquatic organisms (Ebersole et al. 2003), especially cold-adapted species with life history stages having limited mobility (e.g., northwestern North America stream amphibians: Jones et al. 2005; Sagar et al. 2006).

Knowledge gaps remain regarding stream temperature variability at fine spatial scales. Stream temperatures are not well characterized for the smallest streams within networks, despite the ecological and management relevance of headwaters. In the Pacific Northwest, headwater streams are estimated to drain up to 80 % of a catchment area (Gomi et al. 2002) and may provide habitat to unique faunal assemblages (Olson et al. 2007). To our knowledge, only studies by Gravelle and Link (2007), Brown and Hannah (2008), Cadbury et al. (2008), and Snyder et al. (2015) have documented stream temperature variability at multiple locations for zero- and first-order stream networks, whereas most other studies were conducted on second- and higher-order streams (e.g., Rutherford et al. 1993; Arscott et al. 2001; Danehy et al. 2005; Imholt et al. 2013). The study by Gravelle and Link (2007) was primarily focused on forest harvesting, the study by Snyder et al. (2015) focused on a two month summer period in the Appalachian Mountains, and the other two headwater network studies were conducted in glaciated environments (Brown and Hannah 2008; Cadbury et al. 2008), hence their inference to other environments and seasons may be limited. A broader set of studies has been conducted on headwater catchments within the context of forest harvesting (Moore et al. 2005a; Anderson et al. 2007; Rykken et al. 2007; Groom et al. 2011); however, these studies were focused on the response to harvesting for individual reaches and did not consider thermal variability across headwater networks.

The majority of regional and sub-regional stream temperature studies have focused on summer periods, although a few have examined stream temperature throughout the year (e.g., Moore 2006; Hrachowitz et al. 2010; Arismendi et al. 2013; Imholt et al. 2013; Dick et al. 2015). Summer temperatures are critical for aquatic organism growth and survival, and summer may be the season where thermal thresholds are attained, potentially affecting survival; however, understanding variability in stream thermal regimes during the fall, winter and spring seasons is also important for effectively managing aquatic ecosystems (Beschta et al. 1987; Holtby 1988; Brown et al. 2011; Leach and Moore 2014). In Pacific Northwest headwater basins where cool-water adapted amphibians dominate stream networks (Olson and Weaver 2007; Olson and Burton 2014), spring and fall active seasons may be particularly important for foraging and reproduction, likely in part due to the prevailing cool, moist surface conditions. These species migrate vertically into substrates during warm summer conditions or when their temporary streams dry. Little work has been done to characterize annual thermal regimes of their habitats. Several of these species are regional endemics, adding conservation concern to sustaining critical habitat conditions in landscapes that are actively managed for wood production, and to hedge uncertainties with climate change effects.

In the Pacific Northwest, regional stream temperature studies are being used to assess stream thermal regimes under future climate (e.g., Arismendi et al. 2012, 2013). Arismendi et al. (2012) concluded that there is a need to develop stream temperature sensor networks to develop a better mechanistic understanding of trends. Regionally developed stream temperature models (e.g., Isaak et al. 2011) are being used to inform site management decisions for developing climate-resilient approaches to stream-riparian management (Isaak et al. 2015). It would be valuable to evaluate how such a model performs relative to the observations of reach-scale thermal heterogeneity of headwater stream networks, since this spatial variability may be ecologically important in providing critical thermal refugia under conditions altered by climate and environmental changes.

Using a western Oregon, USA case study to advance our knowledge of headwater stream network temperature patterns we: (1) quantified temperature variability across a forested headwater stream network over a two-year period; (2) examined the relationships of stream temperature patterns with weather, above-stream canopy cover, and geomorphic and terrain attributes; and (3) compared observed headwater stream temperatures to predictions for our study area made by a regional stream temperature model (NorWeST; Isaak et al. 2010, 2011). We addressed these objectives using stream temperature observations made at 48 sensor locations within a managed 128 ha forest in the foothills of the Cascade Range during 2012 and 2013. Our results provide insights on the variability of forested headwater stream temperatures, with implications for model applications and monitoring.

Study area

The study was conducted at the Keel Mountain Study Area, a small forested headwater drainage (128 ha; N44°31′41.0″; W122°37′55.0″) spanning 470 to 765 m elevation on the west slope of the central Cascade Range in Oregon (Fig. 1). The study area comprises lands managed by the US Department of Interior, Bureau of Land Management as one installation of the broader Riparian and Density Management Study (DMS; Cissel et al. 2006). The study area lies within the *Tsuga heterophylla* zone of the western Cascades physiographic province (Franklin and Dyrness 1973). Forests in this zone are dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) with lesser amounts of western red cedar (*Thuja plicata* Donn ex D.), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl), and western white pine (*Pinus monticola* Douglas ex D. Don). The dominant hardwood associates include red alder (*Alnus rubra* Bong) and bigleaf maple (*Acer macrophyllum* Pursh). Douglas-fir frequently dominates locations disturbed in the past 150 years whereas alder is locally abundant in association with more frequently disturbed riparian areas and some upland openings.

The climate is mild, wet maritime with substantial variability tied to elevation and location. Precipitation typically ranges from 1650 to 3000 mm per year with more than 90 % occurring in winter months (Franklin and Dyrness 1973). The study area occurs within a rain-snow transition zone, thus snow occurs, but varies among years. Mean air temperatures range about 8–9 °C annually and about 1–2 °C in January; mean daily maximum temperatures in August range about 27–29 °C (Franklin and Dyrness 1973).

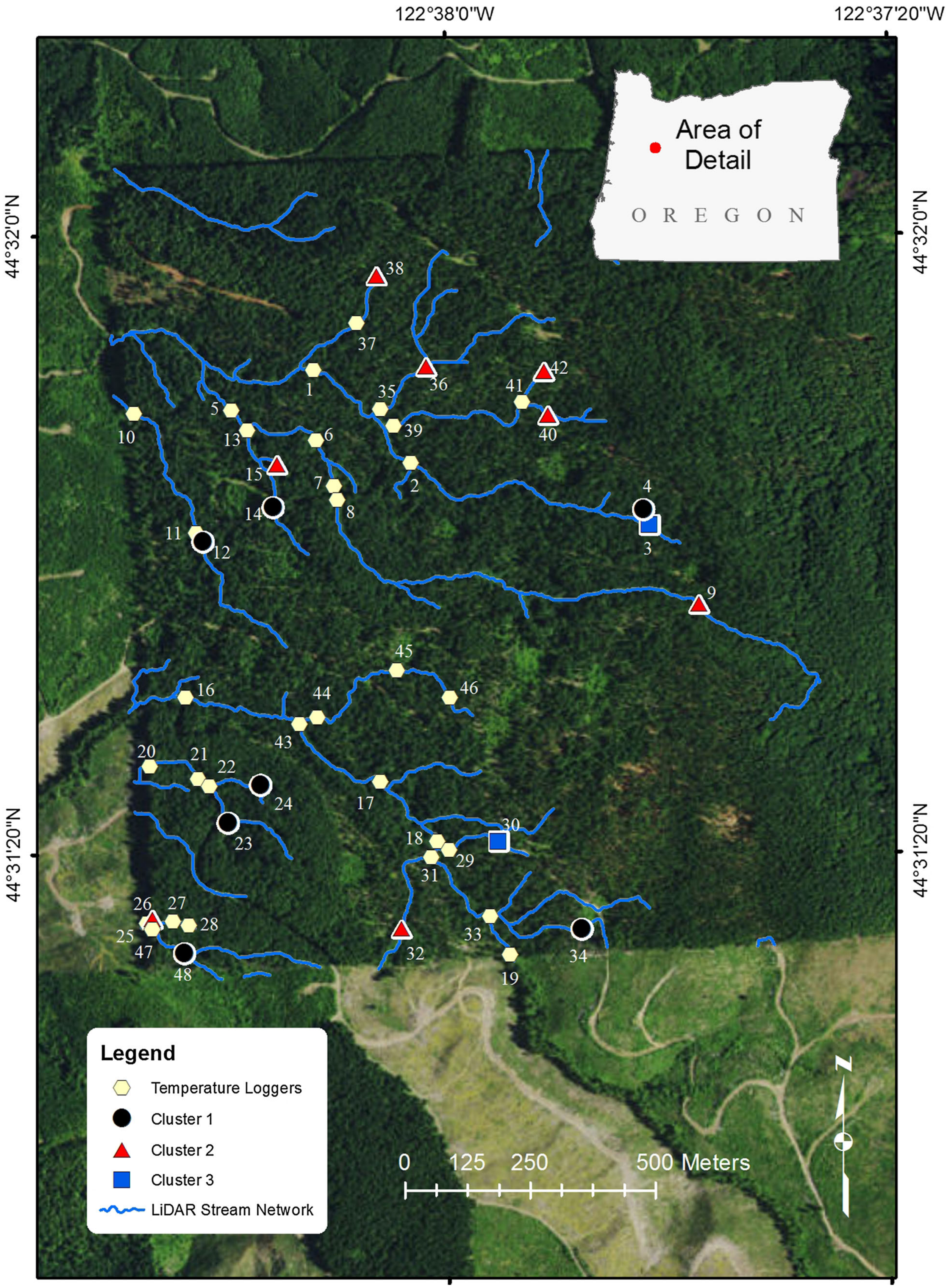
Surface geology consists of undifferentiated tuffaceous sedimentary rocks, tuffs, and basalt (Cissel et al. 2006). Topography consists predominantly of 0–30 % slopes with locally steep (30–60 % slopes) areas associated with the dendritic stream pattern. General aspect of the area varies SW to NW. Soils are deep and moderately deep, well-drained gently sloping to very steep clay loams, cobbly loams, stony loams, and gravelly loams formed in glacial till or colluvium derived from basic igneous rock or tuffaceous rock (Cissel et al. 2006; Langridge 1987).

The study area has been subject to forest harvesting as part of the Density Management and Riparian Buffer Study (Cissel et al. 2006). Harvesting has consisted of upland thinning treatments with riparian buffers. Previous studies conducted at Keel Mountain have addressed the effects of riparian buffer width and upland thinning on a variety of response metrics including riparian microclimate and instream habitats and vertebrates (Anderson et al. 2007; Olson and Rugger 2007; Olson and Weaver 2007; Olson et al. 2007, 2014; Olson and Burton 2014). We explored the potential influence of forest harvesting impacts on stream temperature at Keel Mountain and some of these analyses are included in the supplemental material. Our analyses suggested that forest harvesting at Keel Mountain has had minimal impact on above-stream forest cover and that stream temperature response to harvesting has likely been minor. In the discussion we elaborate on potential implications of forest harvesting at Keel Mountain on interpreting results from this study and associated uncertainties.

Methods

Data sources

Stream temperature Stream temperature was measured (resolution 0.1 °C; accuracy ±0.5 °C) at 15 min intervals



122°38'0"W
122°37'20"W
44°32'0"N
44°31'20"N
Area of Detail
OREGON
Legend
Temperature Loggers
Cluster 1
Cluster 2
Cluster 3
LiDAR Stream Network
0 125 250 500 Meters
N

◀ **Fig. 1** Aerial image of Keel Mountain study area, Oregon, USA. The 17 logger sites included in the example cluster analysis and their resulting cluster class are identified by *circles*, *triangles* and *squares*. Stream network was delineated using the LiDAR derived DEM

using submersible recording dataloggers (MicroTech; MadgeTech Inc., Warner, NH, USA). Factory calibration of new sensors was verified upon receipt by operation in a controlled environment cabinet over an air temperature range of 5–25 °C observed as a repeated sequence of temperature step changes over 72 h.

The Keel Mountain stream network was monitored by placement of in-stream temperature sensors throughout to capture key transitions in the system: (1) just upstream of stream confluences; (2) at longitudinal points where there was a transition in associated upslope buffer and treatment type as part of the harvesting treatments; (3) above road crossings; and (4) at property boundaries. A total of 48 sensor locations were monitored. We report on data collected during 2012 and 2013. Minimal gaps in the stream temperature records were associated with datalogger retrievals, losses or malfunction. Data gaps of a week or less were filled using linear regression models between stream temperature and paired air temperature measurements made at 1 m above the stream.

Sensors were installed with solar radiation shields and were typically attached to a fiberglass rod inserted into the streambed at the nominal deepest point in the stream cross section. The solar radiation shields consisted of white plastic cups inverted over the sensor. Holes were made in the white plastic cups to facilitate water exchange. The sensor was centered within the cup at a height of approximately 2 cm above the lower rim and streambed. Once deployed, dataloggers generally remained in the field and data downloaded on site to a portable computer at approximate 4–10 week intervals. Datalogger batteries were changed at nominal 1-year intervals. Some sites were subject to sensor burial due to accumulation of sediment around the logger. These occurrences were noted during field visits and confounded data were flagged and discarded from analysis.

Air temperature and precipitation We used daily spatially interpolated air temperature and precipitation estimates extracted from Daymet (Thornton et al. 2014) to relate stream temperature patterns to general weather conditions at the Keel Mountain study area. Daymet provides estimates of daily weather parameters on a 1 km by 1 km grid for the conterminous United States, Mexico, and southern Canada. At the time of submission, Daymet weather products were available for the period of January 1, 1980 to December 31, 2014. We selected air temperature and precipitation for the 1 km by 1 km grid cell covering the Keel Mountain study area. We calculated mean daily air temperature as the average of daily maximum and minimum air temperatures provided from Daymet. We also calculated cumulative precipitation from Daymet for one to seven day lags from the day of interest as indicators of catchment wetness. Air temperature was also measured at Keel Mountain 1 m above the stream at the same locations as the water temperature sites using shielded temperature loggers; however, we used Daymet temperatures for most of our analysis for three reasons: (1) Daymet allowed us to use a common reference across all our sites; (2) Daymet allowed us to place our 2 years study within a longer climatic record (1980–2013); and (3) Daymet provided an adequate representation of local air temperature conditions at Keel Mountain. We compared Daymet mean daily air temperature to the measured above-stream air temperatures. For most sites and most periods, above-stream and Daymet mean daily air temperatures were typically within 3 °C of each other and exhibited similar seasonal patterns; however, Daymet temperatures exceeded above-stream temperatures by up to 5 °C during summer, which is a bias consistent with comparing open and below canopy air temperature measurements (Benyahya et al. 2010). We did not have information on snowfall or accumulation for the study area and this represents a source of uncertainty in interpreting our results.

Geomorphic attributes and above-stream canopy cover We explored relations between observed stream temperature patterns and various geomorphic attributes (stream width, elevation, slope, aspect, catchment area, dominant streambed substrate, and terrain sky view factor) and above-stream canopy cover. A number of geomorphic attributes were calculated from a LiDAR-derived digital elevation model (DEM). A bare earth grid was computed from a LiDAR survey (conducted between September 21st and November 27th, 2012) with 3 ft (0.91 m) cell size. Using the LiDAR-derived DEM, we calculated elevation, catchment area, local slope, aspect, and terrain sky view factor for each site. Catchment area was calculated using the deterministic 8 method (O'Callaghan and Mark 1984). Local slope was calculated using the approach presented by Zevenbergen and Thorne (1987). Terrain sky view factor was calculated using the approach by Oke (1987). All geoprocessing was done using SAGA 2.1.0 (System for Automated Geoscientific Analyses Geographic Information System 2013). We also made field measurements of wetted stream width for each sensor location. Wetted width measurements were made on a single day, but provide a relative comparison of stream widths across sites. The dominant streambed substrate for each site was classified into three categories: coarse (>16 mm diameter), which included coarse gravel, cobble, and boulder class sizes; medium (4–16 mm diameter), which included fine and medium gravel size classes; and, fine (<4 mm diameter), which included clay, silt, and sand size classes.

Hemispherical canopy images were used to compare above-stream canopy cover between stream temperature measurement locations. A 180° fisheye lens and Nikon Coolpix P900 were used to capture images. Images were taken approximately 1 m above the stream surface at each sensor location. These images represent local above-stream canopy cover conditions and do not account for potential differences in canopy cover upstream of the sensor. Although the images were captured during March 2015, they should provide a reasonable relative comparison of above-stream canopy cover between locations since riparian vegetation structure has likely remained consistent between 2012 and 2015 since no major vegetation disturbances have occurred in the riparian zones during that time. In addition, seasonal variation in canopy cover was likely modest as coniferous species dominate the riparian zones with deciduous species occurring in low abundance (2–10 % of stems per acre; Marquardt et al. 2012).

Above-stream sky view factors were derived by analyzing the hemispherical images with Gap Light Analyser (GLA) software (Frazer et al. 1999) using 5° increments for both zenith and azimuth angles. The sky view factor (f_v) was computed following (Moore et al. 2005b; Leach and Moore 2010):

$$f_v = \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2} g_*(\theta,\psi)\cos\theta\sin\theta \cdot d\theta \cdot d\psi \quad (1)$$

where θ is the solar zenith angle (vertical = 0), ψ is the azimuth angle, and $g_*(\theta,\psi)$ is the gap fraction at sky position θ, ψ. The double integral was approximated by summations using an interval of 5 ° for both zenith and azimuth angles.

Analysis

Stream temperature data were analyzed in two sets to address the objectives of this study. The first set focused on all 48 stream temperature observation sites and was used to examine spatial and seasonal stream temperature patterns and to compare mean August site conditions to the mean August NorWeST regional stream temperature model (Isaak et al. 2010, 2011). Using this set, we also conducted spatial statistical modelling to relate stream temperature patterns to site characteristics (elevation, stream width, catchment area, slope, aspect, channel substrate, and terrain shading). The spatial statistical modelling suggested that these site characteristics, as well as forest harvesting treatments, could not explain the variability in stream temperature (details provided in the supplemental material). Therefore, we used subsets of the 48 sites that focused on different permutations of upstream sensor locations from zero- and first-order streams that were flow-unconnected across the observation network (i.e., sensor was not connected upstream along the stream network to another sensor from the subset). Since these sites were flow-unconnected, we could assume greater spatial independence between sites than if the sites were located on flow-connected channels. Seventeen locations was the maximum number of sites we could subset from the full 48 sites while still maintaining flow-unconnected conditions. A total of 3456 combinations of 17 flow-unconnected sites were possible for our stream network. These flow-unconnected sets were used to classify the stream temperature patterns using a cluster analysis, and to compare site characteristics among the stream temperature clusters.

Seasonal and spatial thermal patterns Seasonal mean stream temperatures were calculated for each of the 48 stream temperature observation sites for the 2012 and 2013 calendar years. The mean for all sites was calculated for each season and year combination. For each site, season, and year combination, the departure from the overall seasonal mean was calculated and used to generate maps to show spatial structure in stream temperature across seasons. We classified winter as January, February and March; spring as April, May, and June; summer as July, August, and September; and fall as October, November, and December. We chose this classification primarily because July, August, and September were the months with the highest air and water temperatures, and January, February, and March were generally the months with the lowest air and water temperatures (Fig. 2). Sites missing at least 10 % of the record for a season and year combination were removed from the analysis, which resulted in the following number of sites removed: winter 2012 = 1, spring 2012 = 2, summer 2012 = 4, fall 2012 = 1, winter 2013 = 1, spring 2013 = 0, summer 2013 = 0, fall 2013 = 1.

Upstream thermal variability and site characteristics We initially used spatial statistical models and the stream temperature measurements made at the 48 sites to make inferences between stream temperature variability and relationships with site characteristics. Our results suggested that there was little support for including any of the site characteristic predictor variables in a final model to describe spatial stream temperature patterns at this study area. Details on these analyses are included in the supplemental material.

A major limitation of the spatial statistical modelling was that we used summary metrics of the annual stream temperature regimes (e.g., mean annual stream temperature, standard deviation of mean daily stream temperature, maximum weekly average temperature) as response variables in the models. These summary metrics do not capture the full variability in annual stream temperature patterns. Therefore, we applied cluster analysis (Johnson and Wichern 2002) since it considers the similarity of the entire stream temperature regime between sites. For this analysis

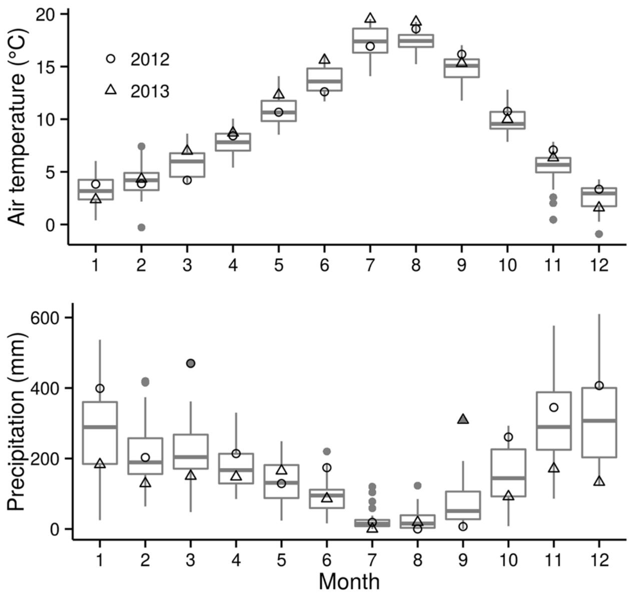


Fig. 2 Boxplots of historic (1980–2013) monthly air temperature and precipitation for Keel Mountain study area, Oregon, USA, extracted from Daymet. *Circles* and *triangles* represent Daymet values for the 2012 and 2013 study years, respectively. *Solid grey points* are boxplot outliers (greater than or less than 1.5 times the interquartile range)

it was critical to minimize the influence of spatial correlation; therefore, we examined all permutations of 17 stream head site subsets in our network that were flow-unconnected and had minimal data gaps. The reach containing sites 44, 45 and 46 was not included in the analysis due to extended data gaps in these records. In addition, site 19 was also excluded, since it is downstream from a clearcut that is located outside of the study area boundary. We were concerned that this site may be influenced by the clearcut and would confound our ability to compare it to the other sites within the study. There were 3456 unique permutations of the 17 flow-unconnected sites; therefore, we only show results using the subset of sites 3, 4, 9, 12, 14, 15, 23, 24, 26, 30, 32, 34, 36, 38, 40, 42, 48 (Fig. 1) and discuss the robustness of the conclusions derived from this subset within the wider range of possible permutations.

The 17 site subsets were selected to explore variability in headwater stream temperature and relate these stream temperature patterns to landscape position. Daily mean stream temperature records were generated from the sub-daily observations and were used to calculate summary statistics and generate graphics documenting spatial and temporal thermal variability. We also used above-stream air temperatures, DayMet mean daily air temperature and precipitation output to explore whether spatial variability in the upstream stream temperature sites was related to meteorologic conditions. Specifically, we compared daily spatial range in stream temperature to mean daily air temperature and one to seven day cumulative precipitation totals, as an indicator of catchment wetness.

We performed a cluster analysis using the 17 flow-unconnected upstream site subsets in order to group sites based on similar annual thermal patterns. Complete linkage clustering was performed on time series of mean daily temperature using hierarchical cluster analysis (Johnson and Wichern 2002) in R (R Development Core Team 2014). The clustering algorithm takes the distance matrix computed for daily stream temperatures from the 17 sites and first assigns each site to its own cluster and then iteratively joins the two most similar clusters until a single cluster is formed. We chose to trim the cluster analysis to three clusters to classify the stream temperature sites. The choice of three clusters was based on examination of within cluster variability while also aiming to not overfit the dataset. The cluster analysis was performed independently on 2012 and 2013 years. We compared how site characteristics varied between the three clusters.

Regional stream temperature model comparison We compared stream temperature measured in our study to predictions made for the Keel Mountain area by the NorWeST regional stream temperature model, which is an empirical model used to make stream temperature predictions for streams in the Pacific Northwest (Isaak et al. 2010, 2011). We extracted from the NorWeST online database the modelled historic (based on a composite of years between 1993-2011) mean August stream temperature for the NorWeST stream segment within the Keel Mountain study area. No observations from within our study area were used to fit the NorWeST model. NorWeST does not predict stream temperatures for the entire stream network at Keel Mountain, but only for one of the stream segments [the reach that includes sites 1, 2 and 3 (Fig. 1)]. We compared the NorWeST stream temperature prediction against observations for the entire stream network since certain fauna, such as fish and amphibians, would not be restricted to this single reach and could search out optimum thermal habitats across the stream network. The NorWeST predicted historic mean August stream temperature for Keel Mountain is 12.93 °C with a root mean square error (RMSE) of 0.92 °C. NorWeST database does not provide prediction limits for modelled stream temperatures; therefore, we approximated prediction limits as ±2 RMSE (±1.84 °C).

Results

Overview of the study period

To place our 2012 and 2013 stream temperature data within a broader climatic context, we compared DayMet air temperatures from these years to long-term (1980–2013) weather data extracted from the DayMet database for the Keel Mountain study area (Fig. 2). Monthly air temperatures during 2012 were within the middle 50 % of historic values except during late summer and early fall when air temperatures were greater than historic averages. During 2013, air temperatures were greater by about 1.5–3.5 °C than historic averages during spring and summer. The 2012 year was overall wetter than 2013 (2628 and 1585 mm year^{-1}, respectively).

Seasonal and spatial thermal patterns

Departures of individual site stream temperatures from the overall mean for each season and year combination showed consistent patterns between years for the four seasons (Fig. 3). Spatial structure in stream temperature was most evident during fall, winter, and spring. During both fall and winter, the most northern tributary and its headwater sites were 1–4 °C greater than stream temperatures at most of the remaining sites. Spatial variability during spring was minimal as nearly all sites were within 1 °C of the seasonal overall mean. Spatial variability in stream temperature was greatest during summer (up to a spatial range of 4.6 °C in mean summer temperature) and the general network patterns seen during fall and winter were replaced by greater patchiness in stream temperature patterns across the network. Seasonal spatial variability was consistent between years despite 2013 being overall a warmer and drier year than 2012 (annual air temperature of 9.7 °C for 2012 and 10.2 °C for 2013).

Upstream thermal variability

Spatial thermal variability There were 3456 different permutations of the 17 upstream flow-unconnected sites that were analyzed. Results shown are an example from only one subset, but results from the remaining subsets were generally consistent with those results shown here. Spatial variability in daily stream temperature across the Keel Mountain study area captured by the 17 upstream-most sites was greatest (up to 9.8 °C) during late summer months and lowest (2.0–2.5 °C) during fall and spring (Fig. 4, upper and middle panels). There were some

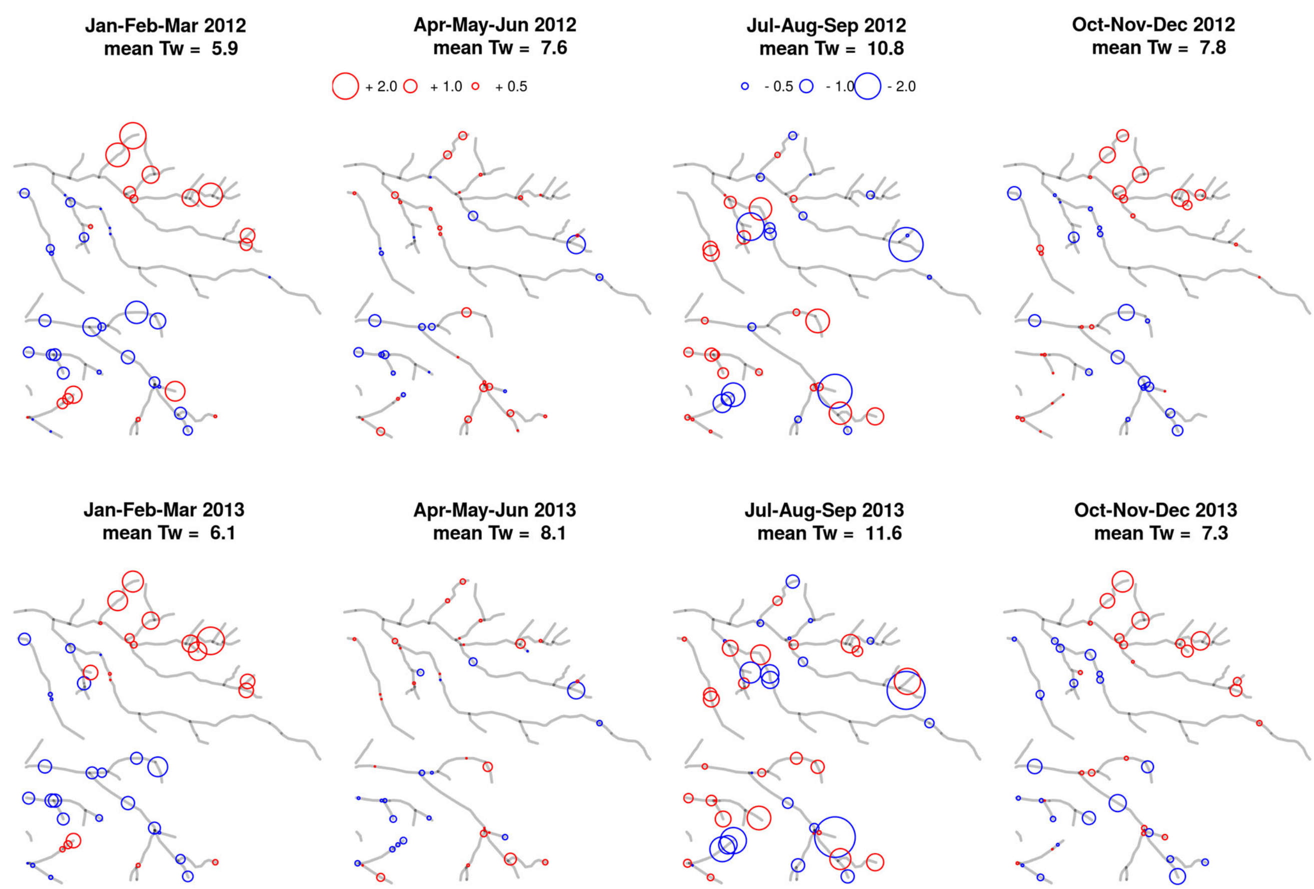


Fig. 3 Maps of seasonal stream temperature (Tw; °C) departures from the seasonal means for the Keel Mountain site, Oregon, USA, for 2012 and 2013. *Red* (*blue*) *circles* indicate that stream temperature was greater (less) than the seasonal mean. *Grey lines* represent the stream channel network

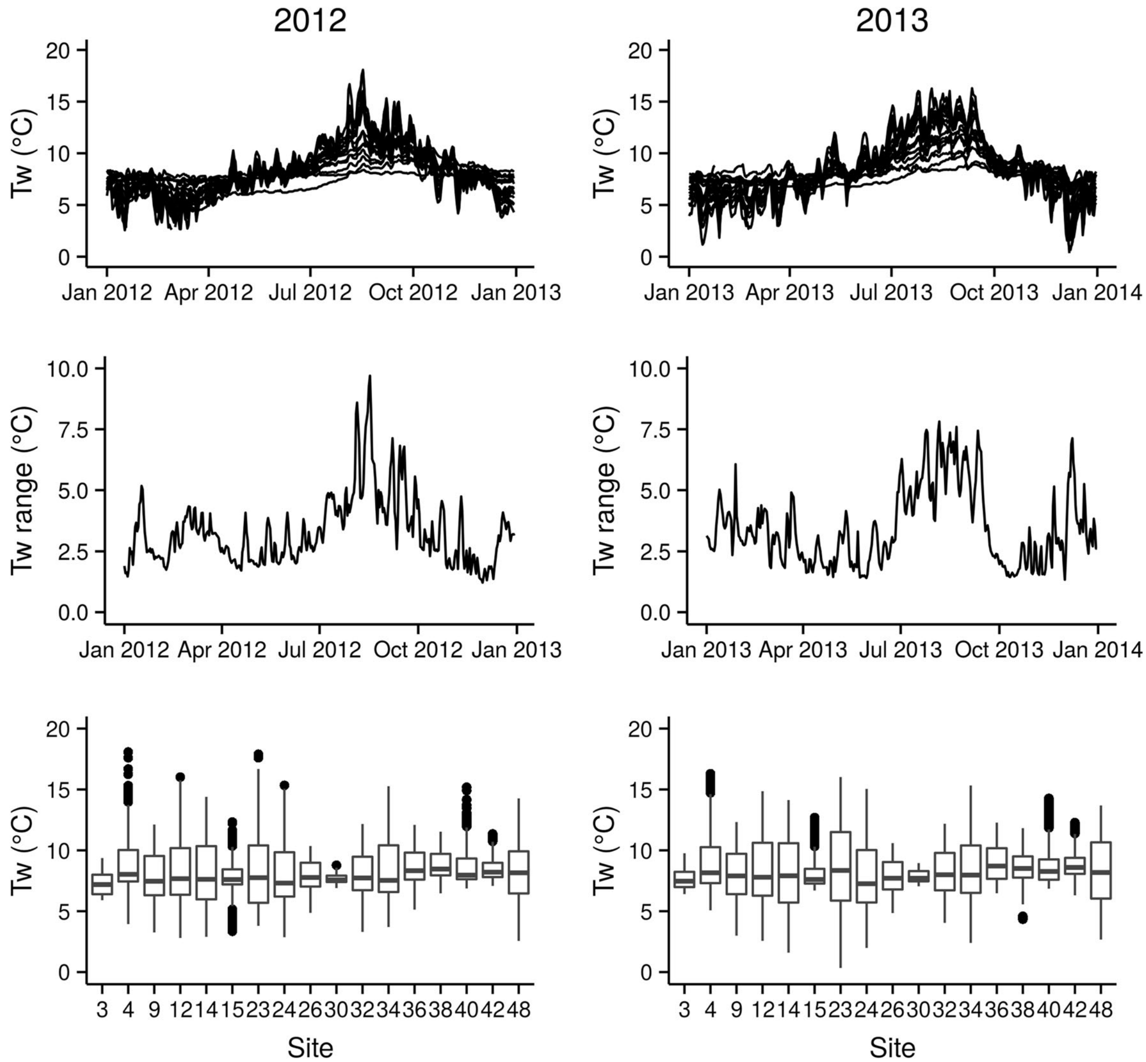


Fig. 4 Time series of mean daily stream temperature (Tw) at each of the 17 upstream locations for 2012 and 2013 (*top*); range in mean daily stream temperature across the 17 upstream sites (*middle*); and boxplot of mean daily stream temperature for the year for each site (*bottom*)

periods during winter when the daily range in stream temperature was of similar magnitude to summer ranges, particularly during December 2013. Among sites, annual variability in daily stream temperature was evident during 2012 and 2013 (Fig. 4, boxplots in lower panel). Certain sites were relatively invariant and only ranged around 2–4 °C during the year (e.g., sites 3 and 30), while other sites varied up to 10 °C throughout the year (e.g., sites 4, 12, 14, 23, 24).

Spatial range in stream temperature was greatest during periods of high (>15 °C) and low (<5°C) air temperatures and lowest during moderate (7–12 °C) air temperatures (Fig. 5). In addition, the greatest spatial stream temperature ranges were associated with dry periods. In contrast, wetter periods (three day cumulative precipitation greater than 50 mm) consistently exhibited spatial stream temperature ranges below 5 °C. Only three day cumulative precipitation is shown in Fig. 5, as one to seven day cumulative precipitation showed generally similar patterns.

Cluster analysis Hierarchical clustering was used to separate the 17 upstream sensor sites into three groups. For the example subset, cluster 1 contained 7 sites (4, 12, 14, 23, 24, 34, and 48), cluster 2 contained 8 sites (9, 15, 26, 32, 36, 38, 40, and 42), and cluster 3 had 2 sites (3 and 30). For the most part the clusters were not grouped spatially, although sites 36, 38, 40, and 42 in cluster 2 were grouped together in the northern region of the study site. Clustering results were consistent between 2012 and 2013.

The time series plot of daily stream temperature for sites within the three clusters (Fig. 6) shows the temperature patterns during 2012 and 2013. Cluster 1 included the most thermally dynamic sites characterized by the highest summer stream temperatures (annual daily maximums >14 °C in 2012) and lowest winter stream temperatures

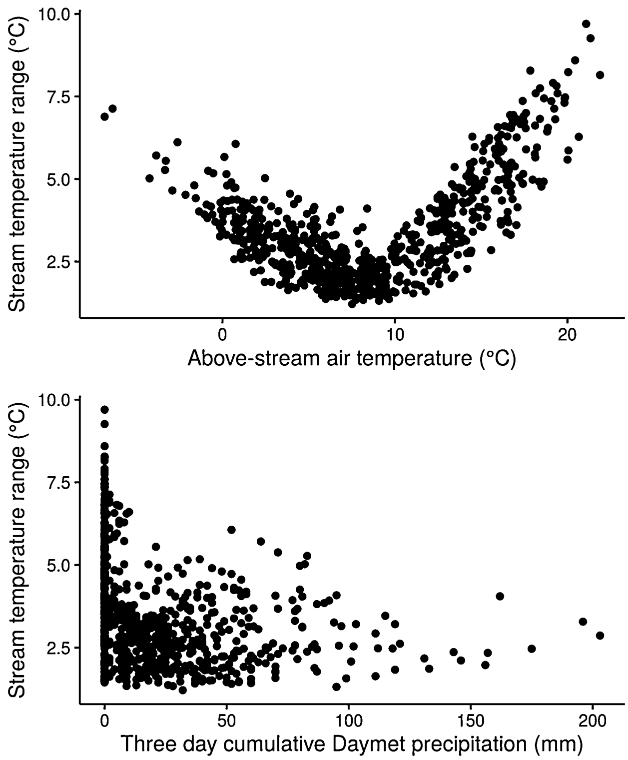


Fig. 5 Daily stream temperature range across the 17 upstream sites for 2012 and 2013 plotted against above-stream daily air temperature (*top*) and Daymet three-day cumulative precipitation (*bottom*)

(annual daily maximums <5 °C). Cluster 2 included sites that were generally more stable than cluster 1 sites, having relatively lower summer stream temperature peaks (around 10 °C) and higher winter stream temperatures (around 5–8 °C). Cluster 3 included the two sites (3 and 30) that were substantially more stable than any of the other sites monitored during the study period.

Geomorphic attributes and above-stream canopy cover The eight geomorphic and above-stream characteristics that we assessed (slope, elevation, aspect, catchment area, stream width, terrain-only view factor, terrain and vegetation view factor, and streambed substrate) were highly variable among clusters for both the example subset shown in Fig. 7 and the remaining subset permutations. For the example subset, cluster 1 sites were generally characterized by lower slopes, wider stream widths, and higher terrain-only view factors compared to cluster 2 sites. In addition, cluster 1 sites were generally west-facing and cluster 2 sites were generally south- and southwest-facing; however, these relationships were weak and only aspect ($p = 0.048$) and terrain view factor ($p = 0.033$) were significantly different at an α of 0.05. In addition, when other permutations of the 17 sites were analyzed, these relationships were often not found to be statistically significant. The catchment area, elevation, dominant streambed substrate, and terrain and vegetation view factor distributions between clusters 1 and 2 were similar. View factors accounting for both terrain and vegetation determined from the hemispherical images were generally similar between clusters 1 (mean of 0.33) and 2 (mean of 0.26). Site 36 in cluster 1 had a view factor of 0.81, which was substantially greater than any other sites. Cluster 3 was omitted from this analysis because it had only two sites.

Regional stream temperature model comparison

The mean August stream temperature for the Keel Mountain study area predicted by the NorWeST model fell near the mode of both the 2012 and 2013 August means for the 48 sensor sites (Fig. 8). Although the NorWeST prediction captured the central distribution of stream temperatures observed at Keel Mountain, observed temperatures across the stream network were up to 2.8 °C lower and 0.6 °C higher than the approximated prediction limits (11.09, 14.77). Of the total 48 sites, 12 had mean August stream temperatures below the lower prediction limit in both 2012 and 2013, and one site was 0.6 °C above the upper prediction limit in 2013. Three of the 12 sites that fell below the prediction limits were clustered together on the same reach in the southwest corner of the study area (sites 26, 27, 28). The remaining sites were distributed throughout the stream network channel and occurred near the head of stream reaches (sites 3, 9, 15, 19, 26, 27, 28, 30, 32, 38, 42), although some sites (7 and 8) occurred on main channels.

Discussion

Seasonal and spatial thermal variability

This study highlights that stream temperature of forested headwater streams can be highly variable over relatively small areas and that the degree of variability is seasonally dependent. The spatiotemporal stream temperature patterns we observed in this study were consistent with current understanding of energy exchange processes for small streams developed from detailed reach-scale energy budget studies (Brown 1969; Webb and Zhang 1999; Johnson 2004; Hannah et al. 2008; Leach and Moore 2011; MacDonald et al. 2014; Leach and Moore 2014). Keel Mountain is characterized by warm and dry summers; therefore, during the summer the study streams likely experience relatively high insolation at the stream surface and low streamflow conditions, and thus low channel water volumes and low velocities. As the observed summer patterns show, we might expect greater stream temperature spatial variability due to local site conditions (e.g., canopy

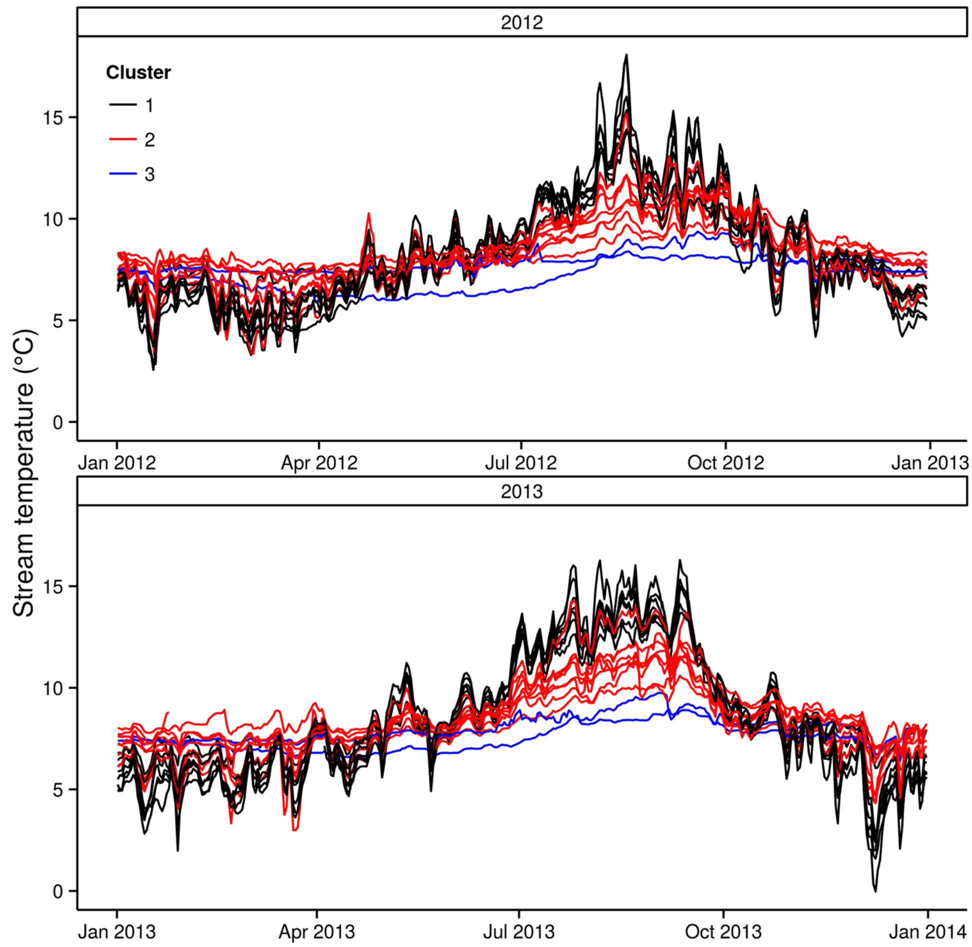


Fig. 6 Time series of 2012 and 2013 mean daily stream temperatures for the 17 upstream sites coloured by cluster

cover, sky view factor, aspect, slope, groundwater-surface water interactions) controlling the magnitude of energy fluxes at this time of the year. Because water volumes in the channel are low during summer, these differences in local energy exchanges are able to translate into more pronounced stream temperature differences than during seasons characterized by higher water volumes.

The minimum spatial stream temperature range occurred at air temperatures around 8–9 °C (Fig. 5). These air temperatures are similar to the long-term (1980–2013) mean estimated air temperature for this area (9.5 °C) and mean stream temperature for all sites for both 2012 and 2013 (8.2 °C). These values likely approximate the temperature of groundwater discharge (Meisner et al. 1988); therefore, the minimum stream temperature range at these air temperatures likely reflect the transition periods between summer and winter when streams dominated by groundwater contributions and those dominated by surface energy exchanges will be most similar.

In contrast to dry summer periods, the relatively wet periods during fall, winter, and spring are characterized by high streamflow conditions, high water velocities, and low insolation at the stream surface. Therefore, stream temperature across the study site was likely dominated by advection from hillslope runoff which would be a function of the incoming rain temperature and would be relatively uniform across a small area such as Keel Mountain (Leach and Moore 2014). Exceptions would be during cold high pressure weather systems during winter. These events would be characterized by low streamflow and there would be considerable longwave radiation loss at the stream surface (Leach and Moore 2014). Similar to low flow summer periods, there is an emergence of greater spatial variability as a result of low water volumes and differences in site conditions controlling the local energy exchanges.

Snow is known to have an influence on headwater stream thermal regimes in the Pacific Northwest (Leach and Moore 2014, 2015); however, we did not have information on site-specific snowfall or accumulation for the study period. Some of the spatial variability observed during winter periods may be due to some sites being influenced by snow or runoff from snowmelt. This influence may have been minimal, since the sites are located across a relatively minor elevation gradient (615–751 m); however, these mid-

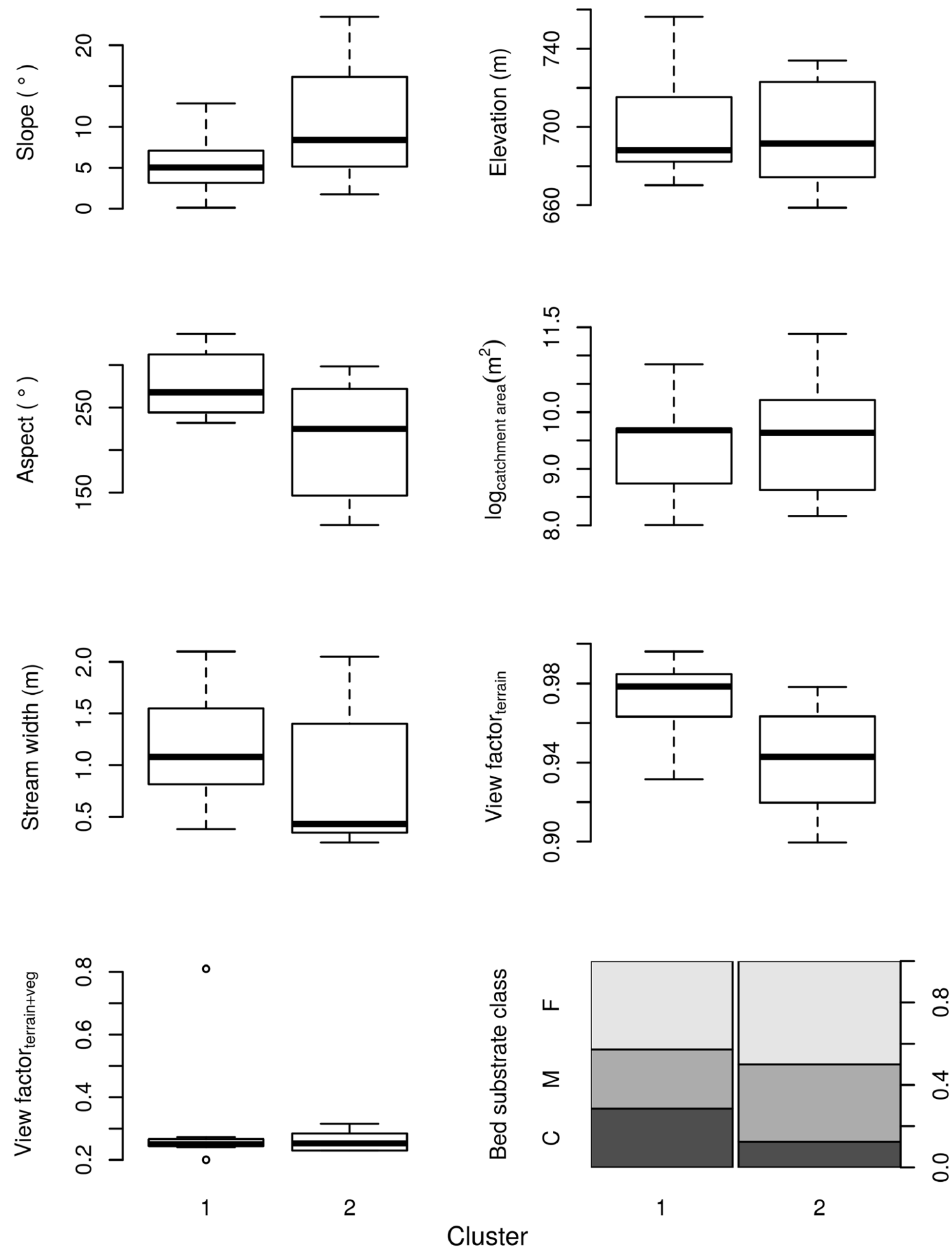


Fig. 7 Boxplots of slope, elevation, aspect, logarithm of catchment area, stream width, and view factors for terrain only and terrain and vegetation, as well as a mosaic plot of dominant streambed substrate (*C* coarse, *M* medium, *F* fine) for stream temperature clusters 1 and 2. Cluster 3 is not shown since it had only two sites

elevation zones can experience considerable variation in snowfall and accumulation over small elevation gradients (Perkins and Jones 2008). In addition, it was unlikely that these streams froze or had significant ice development, as hourly stream temperature records for all sites fell below 1 °C less than 0.5 % of the time.

The comparison of site characteristics between clusters suggests that these landscape properties were weak predictors of spatial stream temperature variability of these headwater streams. In addition, the spatial statistical modelling we conducted also suggested that none of the predictor variables we considered were useful in explaining different metrics of annual stream temperature regime (see supplemental material). These findings are in contrast to empirical regional-scale studies, where slope, aspect, sky view factor, elevation, and catchment area were found to explain observed stream temperature patterns (Scott et al. 2002; Wehrly et al. 2009; Daigle et al. 2010; Hrachowitz et al. 2010; Mayer 2012; Moore et al. 2013). Our study did not sample a sufficiently wide range in predictor variable values to detect a robust thermal signal. However, the cluster analysis highlights that there were distinct thermal regimes that contributed to considerable spatial variability observed for Keel Mountain. For example, sites 3 and 30

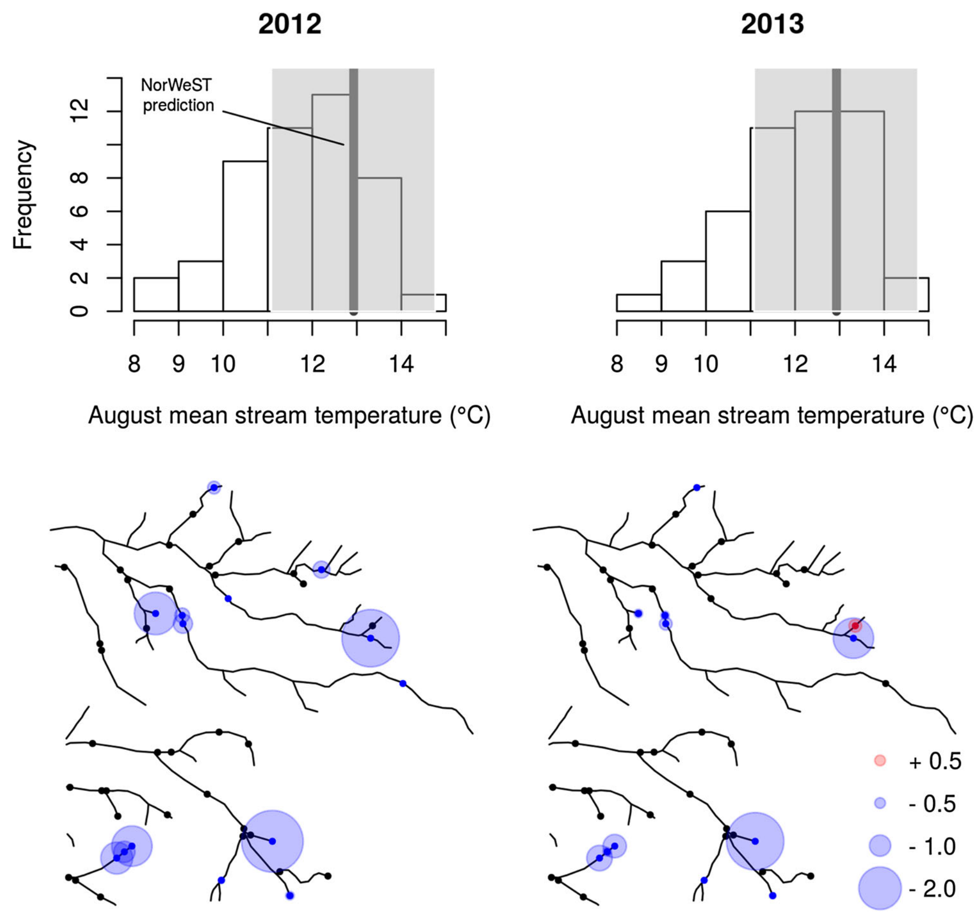


Fig. 8 *Top row* Histograms of observed mean August stream temperatures for all sites from Keel Mountain for 2012 (*left*) and 2013 (*right*), and mean August stream temperature predicted for Keel Mountain by the NorWeST regional stream temperature model (*thick grey line*, 12.93 °C) with prediction limits (*grey band*, 11.09–14.77 °C). *Bottom row* maps of those sites with observed mean August stream temperatures that are less (*blue*) or greater (*red*) than the NorWeST prediction limits. *Black points* indicate sites that are within the prediction limits

(cluster 3) were thermally unique in terms of their relatively stable temperatures compared to the other sites, and likely reflect discrete groundwater discharge zones (e.g., Leach and Moore 2011; Snyder et al. 2015). Our results suggest that predicting spatial thermal variability at headwater stream network scales requires further process-based understanding and better predictors that reflect this understanding, rather than adoption of those predictors used in previous studies at landscape scales. For example, hyporheic exchange is known to be a dominant control on stream temperature for small headwater streams (Story et al. 2003; Hester et al. 2009); however, easily collected or readily available variables to represent this energy exchange process are lacking.

Our study area has been subject to forest harvesting and it is possible that some of the observed spatiotemporal stream temperature patterns are partly due to the influence of harvesting. We attempted to account for potential influence of forest harvesting on stream temperature patterns using spatial modelling approaches (see supplemental material). We included riparian harvesting treatments as categorical variables in the model. Including the treatments as covariates in the spatial models did not help explain the observed stream temperature spatial variability. This was not surprising because earlier analysis of stream temperatures of this and other study areas in the DMS did not report changes with buffers and harvest (Anderson et al. 2007). There were only minor differences in above-stream canopy cover between harvesting treatments at Keel Mountain, as determined from analysis of hemispherical images taken at the stream surface in 2011 (P.D. Anderson, unpublished data) and additional above-stream canopy cover analysis presented in this study. In addition, other studies from the Pacific Northwest that have examined stream temperature response to forest harvesting found minimal to no response for riparian buffer treatments similar to those used at Keel Mountain (Moore et al. 2005a; Gomi et al. 2006). Our analysis suggested stream temperatures were not likely influenced by forest harvesting; however, there were a number of study limitations, including this being a case study with limited treatment replication and no pre-harvest observations of stream temperatures. Although control reaches were included in the analysis, measuring pre-harvest conditions may be particularly important due to the spatial heterogeneity in stream temperatures documented herein.

Regional stream temperature modelling and monitoring

We found that although the NorWeST stream temperature prediction for August for this study area captured the central distribution of observed temperatures, the model prediction limits did not span the full range of observed sub-landscape heterogeneity. In particular, the model did not capture lower stream temperatures even though the 2012 and 2013 study period had two of the warmest mean August air temperatures since 1980 (Fig. 2). This may be due to the model being more robust for higher-order streams in the network and the model error may be underestimated for these first-order streams. Further, the tendency for estimate departures to be greater at stream heads may reflect the NorWeST model dependence on site factors that influence surface water energy exchanges, rather than thermal influences of groundwater interactions. There is likely a bias in the model towards higher-order streams because of the observations and prediction variables used to fit the model. The model representing Keel Mountain was fit to 9218 sites located in a region labelled Oregon Coast that included the lower Columbia, Willamette, northern Oregon coast and southern Oregon coast regions. The observations used to fit the model appear to be primarily from second- and higher-order streams. In addition, some of the predictor variables, such as the 30-m digital elevation model used by NorWeST, may be too coarse in scale to resolve local influences on stream temperature for first-order streams. It may be important to recognize this model bias when using regional scale stream temperature models to predict habitat or aquatic organism distributions under climate and environmental change scenarios (e.g., Isaak et al. 2015), since sub-landscape variability may provide important thermal refugia not accounted for in regional models.

The observed stream network temperature variability documented in this study also has implications for how monitoring programs are designed. We observed mean daily temperature ranges between 2 and 10 °C for all 48 sites during the study period; therefore, deciding on a single representative sampling location for use in a regional stream temperature monitoring program or as part of a management plan will miss substantial variability. Selecting a representative site may be less of a concern if fall, winter or spring stream temperatures are the study focus, since temperatures are more spatially uniform. However, most often the concern is summer temperatures and the summer period can be the season with greatest spatial variability.

Implications for seasonal habitat of cold-adapted biota

Understanding the natural variation in stream temperatures across small spatial scales and among seasons is relevant for understanding the ecology of several cold-water adapted species inhabiting forested headwater stream reaches in the Pacific Northwest. The biotic composition of these streams have only recently been described and details of the physiological ecology of many headwater species relative to temperature are lacking. At the small streams within our case study site, dominant instream fauna include coastal cutthroat trout (*Oncorhynchus clarkii clarkii*), coastal giant salamander (*Dicamptodon tenebrosus*), Cascade torrent salamander (*Rhyacotriton cascadae*), and coastal tailed frogs (*Ascaphus truei*). The latter two species are Oregon State species of concern (Oregon state sensitive, vulnerable; http://www.dfw.state.or.us/wildlife/diversity/species/docs/SSL_by_category; accessed 13 April 2015). The torrent salamander is associated with the smallest streams of headwater networks, often occurring in discontinuous channels of our study sites (Olson and Weaver 2007; Olson and Burton 2014). If reaches dry, these animals migrate vertically into stream substrates to microclimate refugia (Adams and Frissell 2001). Thermal associations are not well known between stream temperature, life history stages, and geographic region, although nuanced relationships likely occur (Hossack et al. 2013). Some known temperature constraints of animals found in our study area include: (1) coastal tailed frog embryo temperature tolerance range of 5–18.5 °C in Washington (Brown 1975) and 2–15.5 °C in California streams (Bury 1968); and (2) the torrent salamander *R. variegatus* was found in streams ranging 6.5–15 °C with thermal stress at 17.2 °C (Welsh Jr. and Lind 1996). According to our sensors, Keel Mountain headwater stream temperatures appear to be within the suitable ranges for these cryophilic organisms, even during summer, with cooler microrefugia likely occurring subsurface. The effect on these animals of the spatiotemporal variation reported here is uncertain, but there may be sublethal effects on developmental rates or surface activity times when animals are foraging and interacting. Amphibians are centrally nested in food webs, and stream temperature variation may have bearing on prey availability or predator activities. Both tailed frogs and torrent salamanders have patchy distributions with elevational and latitudinal constraints, and it is possible that stream temperature variation is a dominant contributor to their distribution patterns.

Whereas further information is scant about effects of temperature on headwater amphibian life history, more is known about cutthroat trout, a diverse group with 14 subspecies in the American West (Behnke 2002). For resident coastal cutthroat trout, those occurring in our study area, spawning occurs when water temperatures reach around 5 °C in the spring (Trotter 2008). Development time of embryos to hatching and of emergence of hatched fry from the gravel are temperature dependent, quantified by degree days (the cumulative sum of mean daily temperature above 0 °C for a given period). For sea-run coastal cutthroat trout, these values range 362–500° days to hatching, which occurs in about 6–7 weeks, and 100–350° days for emergence from the gravel, which occurs by the end of June (see Trotter 2008). Given these spawning dates and hatchout and emergence times in the cooler spring season, and our data showing little variation among stream reaches at that time, it is unlikely that the variation we report among headwater reaches would be significant for the resident trout. Relative to body size, Meeuwig et al. (2004) reported higher temperatures (24 °C) and variable daily temperatures (12–24 °C) negatively affected growth of Lahontan cutthroat trout (*O. c. henshawi*), with a larger effect for larger fish. Hence, their data support sublethal effects of a brief exposure to higher summer temperatures. The lower summer temperatures at our sites should not be directly compared with this study, however, as they may be relatively high for our potentially cooler-adapted subspecies, compared to the Lahontan subspecies which occurs inland in areas achieving much higher summer temperatures. This finding supports the need for further work to understand sublethal effects of higher-temperature stream reaches on resident headwater vertebrates.

Conclusions

We documented spatiotemporal variability of headwater stream temperatures for two years in a managed forested area of western Oregon. Stream temperatures were variable across the measurement network, particularly during summer and dry and cold winter periods, but were less variable during fall, spring and wet winter periods. The sub-landscape variability appeared to be partly associated with water source and landscape position, although site characteristics typically used in regional stream temperature models were not good predictors of thermal variability at headwater scales. Recognizing the seasonal pattern of sub-landscape heterogeneity and associated thermal refugia may be important when designing regional stream temperature monitoring programs and predicting distributions of aquatic organisms under climate and environment change using regional stream temperature models. We highlight that there can be considerable spatial thermal variability at scales not resolved by regional stream temperature models.

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