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Effects of Stream Enhancement Structures on Water Temperature in South Sister Creek, Oregon

Abstract

We evaluated commonly used methods for monitoring stream restorations to inform and improve restoration monitoring and evaluation, using a headwater stream in the Oregon Coast Range as a case-study example. In-stream restoration projects are seldom monitored both pre- and post-restoration. In addition, frequently used low-cost methods may not provide sufficient data to effectively assess trends in stream temperature. Here, we examined what can be learned from temperature loggers installed in the same locations over multiple years in a restored stream. In-stream structures were installed between 2007 and 2011 along a 10-km length of South Sister Creek, Oregon for the purpose of enhancing in-stream habitat. Summer stream temperature data were collected using Hobo Pro-V temperature-logging thermistors at four locations in 2006, prior to restoration, as well as in 2012 and 2013. In 2013, additional temperature loggers were placed within 80 m of the four original loggers to investigate within-reach variability. Although median stream temperatures were highest in 2013 at all four multi-year sites, 7-day maximum temperatures were 4 to 5 °C cooler in post-treatment years than in 2006. Inter-annual variability in stream temperature was more closely linked to inter-annual variability in air temperature and solar radiation than presence of in-stream structures. Thermal heterogeneity was greater in reaches with deeper pools than in bedrock-dominated reaches. Although in-stream structures can create cool microhabitats, they have little influence on mean stream temperature. Longer pre-restoration monitoring and sensor deployment in more varied in-stream habitats would improve our ability to evaluate restoration impacts.

Keywords: habitat restoration, stream temperature, Coast Range, monitoring

Introduction

Stream temperature affects important chemical, physical, and biological processes in aquatic ecosystems (Beschta et al. 1987, McCullough et al. 2009). Recent trend analyses indicate increasing temperatures in the Pacific Northwest (Mohseni et al. 2003, ISAB 2007, Luce et al. 2014) and increased synchronicity between minimum flow and maximum stream temperature that may exacerbate stress on aquatic organisms (Arismendi et al. 2013, Safeeq et al. 2014). Stream temperature has been shown to affect salmonid metabolic rates, growth, and species distribution (Magnuson et al. 1979, Brannon et al. 2004, Allan and Castillo 2007), with extreme maximum daily temperatures linked to impaired egg development, diminished survival rates, and increased risk of disease and mortality (Eaton and Scheller 1996, Richter and Kolmes 2005). Mitigation of stream warming has thus become a critical issue for sustaining native species adapted to historically cooler temperature regimes. Although effects of stream restoration on hyporheic flow and stream temperature have been studied in the eastern US (Crispell and Endreny 2009, Hester et al. 2009, Gordon et al. 2013, Briggs et al. 2018), and numerous studies of stream temperature have been conducted in

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coastal streams of the Pacific Northwest (Ebersole et al. 2003a, 2003b; Johnson 2004; Fullerton et al. 2015, 2018; Reiter et al. 2020), only a few studies have evaluated the effect of in-stream restoration structures on water temperature for streams in the Pacific Northwest (Gendaszek and Opatz 2016). A search of the Web of Science for the period 1965 to 2020 using topic keywords "stream restoration" and "temperature" found 511 articles, yet only three of those papers reported temperature monitoring for in-stream restoration in the Pacific Northwest (Nichols and Ketcheson 2013, Gendaszek and Opatz 2016, Martens et al. 2019).

Several factors influence stream temperature. Stream temperature is directly proportional to the total heat energy delivered to the stream and inversely proportional to water volume. Water source and flow path can influence both seasonal and diel patterns of stream temperature, and increased stream flow tends to decrease stream sensitivity to solar radiation (Tague et al. 2007). The influence of groundwater in moderating stream temperature may be greatest during periods of low discharge. Streams can also be more sensitive to solar radiation at low flow (Burkholder 2007, Jefferson et al. 2008). Hyporheic exchange can also moderate stream temperature, reducing daily maxima, increasing daily minima, and delaying peak daily stream temperatures (Arrigoni et al. 2008, Hester et al. 2009).

In-stream structures such as log jams are thought to affect stream temperature primarily through enhancement of hyporheic exchange (Sawyer et al. 2011). Stream reaches with substantial hyporheic exchange tend to have lower diel ranges of stream temperature and have the greatest lag between peaks in air and stream temperature. Hester and Doyle (2008) identified in-stream structure size, background groundwater discharge rate, and hydraulic conductivity as the most important factors controlling hyporheic exchange, followed by structure type, depth to bedrock, and channel slope. Of structure types studied, channel-spanning structures were most effective at inducing hyporheic exchange. In-stream structures can also change stream bedform and increase pool depth, but these processes are not typically associated with net cooling except where they enhance gravel deposition in reaches previously dominated by bedrock with little hyporheic flow prior to restoration (Crispell and Endreny 2009, Beechie et al. 2013).

In Oregon coastal streams, mean stream temperature tends to increase with distance downstream as a result of exposure of the stream surface to solar radiation and warmer air temperatures (Sullivan et al. 1990, Dent et al. 2008, Groom et al. 2011). However, other work has shown that for some streams, longitudinal trends in temperature are more complex (Fullerton et al. 2015, 2018). Although riparian shade can help maintain cooler stream temperatures in lower-order streams (Brown 1969, Sinokrot and Stefan 1993, Johnson 2004, Meleason and Quinn 2004, Rutherford et al. 2004, Reiter et al. 2020), as stream width-to-depth ratio increases, the relative influence of riparian shade on stream temperature decreases.

The longitudinal thermal gradient serves as a backdrop to thermal heterogeneity operating at finer resolution. Several studies have found temperature anomalies—patches in which water is warmer or colder than ambient stream temperature (Torgersen et al. 2001, Ebersole et al. 2003b, Burkholder 2007, Dugdale et al. 2013)—owing to features such as topographic shade, slope, valley and channel shape, tributary junctions, side-channel habitats, and presence of seeps. Others have investigated the effects of differences in substrate (Johnson 2004) or the presence of in-stream structures, such as channel-spanning logs (Hester and Doyle 2008, Sawyer et al. 2011, Gendaszek and Opatz 2016). Although thermal heterogeneity can be exploited by fish to avoid heat stress and for metabolic advantage (Armstrong and Schindler 2013), it can also complicate stream temperature monitoring.

We investigated the effect of in-stream restoration on stream temperature for South Sister Creek, a forested headwater stream that drains a 30 km^2 watershed within the Oregon Coast Range. South Sister Creek is a second-order stream, and is a tributary to the West Fork of the Smith River in the Umpqua River basin. We compared monitoring data collected by a local watershed

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association in 2006 (prior to restoration) and 2012 (post-restoration) with data we collected in 2013 at these same monitoring sites, using the same methods. We examined changes in stream temperature over time, asking:

1. Do stream temperatures at the four sites monitored over multiple summers indicate consistent patterns of cooler water temperatures following restoration?
2. Are patterns in stream temperature consistent with those expected if hyporheic flow has increased?
3. How variable is stream temperature within the reaches where monitoring loggers have been installed (within 80 m of logger)?

A specific objective of this research was to investigate the utility of methods currently used by many watershed councils and agencies in efforts to evaluate restoration effectiveness. Although many high-resolution methods are available for investigations of stream temperature, such as distributed temperature sensing with fiber-optic cable (Gendaszek and Opatz 2016) or data collection via airborne infrared sensors (Loheide and Gorelick 2006), those methods are costly, time-intensive, and usually beyond the budgets and expertise of watershed council staff and local agencies involved in restoration. We sent an email poll out to the 72 unique addresses for Oregon Watershed Councils listed on the Oregon Watershed Enhancement Board (OWEB) website asking about methods used in monitoring stream temperature. We received responses from 28 of 72; 57% of respondents (n=16) monitor stream temperature, and of those, 14 of 16 get their temperature data from stream gage pressure transducers and/or seasonally deployed logging thermistors such those used on South Sister Creek. Thus, an important goal of this study was to investigate both the utility and the limitations of temperature loggers commonly used in monitoring stream temperature.

Methods

Study Area

Nested in the Umpqua River Basin in the Oregon Coast Range, the forested watershed drained by South Sister Creek (a tributary to the Smith River) is about 30 km^2 in area (Figure 1). Several native fish species occur in the creek, including coho salmon (*Oncorhynchus kisutch*), steelhead (*O. mykiss*), Pacific lamprey (*Entosphenus tridentatus*), brook lamprey (*Lampetra richardsonii*), and anadromous and resident cutthroat trout (*O. clarkii*). The climate of the Oregon Coast is characterized by moderate, wet winters and cool, dry summers. Precipitation in the South Sister Creek watershed averages 155 to 160 cm per year (PRISM 2021). Although South Sister Creek is an ungaged stream, a stream gage was installed on North Sister Creek, in the watershed adjacent to South Sister Creek watershed, in 2012. The two watersheds are similar in area (North Sister Creek watershed is about 10% smaller, at 27 km^2). On an annual basis, the average of the mean discharge for the previous seven days is 1.41 m^3 s^{-1} for North Sister Creek; whereas average discharge in September (at low flow) is about 0.06 m^3 s^{-1}.

Stream channels in the Smith River sub-basin are dominated by bedrock of the Tyee formation that underlies much of the Oregon Coast Range (Seidl and Dietrich 1992). The use of waterways to convey logs, and removal of large wood from streams in efforts to enhance fish passage (a practice referred to as "stream cleaning"), have also contributed to bedrock dominance in many Oregon coastal streams (Kobor and Roering 2004, Miller 2010). Within the last 100 years, the South Sister Creek catchment experienced severe fire, salvage logging, and several management interventions. Much of the watershed burned in the Oxbow fire of 1966, followed by salvage logging that removed most of the forest cover in the burned area. Two years after the fire, the Bureau of Land Management (BLM) conducted post-harvest surveys of South Sister Creek and reported increased silt, numerous log jams, and high water temperatures that ranged from morning temperatures of 17 °C near the confluence with the Smith River, to 29 °C above the confluence with Bum Creek in August 1968 (BLM 1968, 1969). In the 1970s and 1980s, South Sister experienced "stream cleaning" (BLM 2009). The BLM later identified the "lack of in-stream structure and young age of surrounding riparian trees, combined with the

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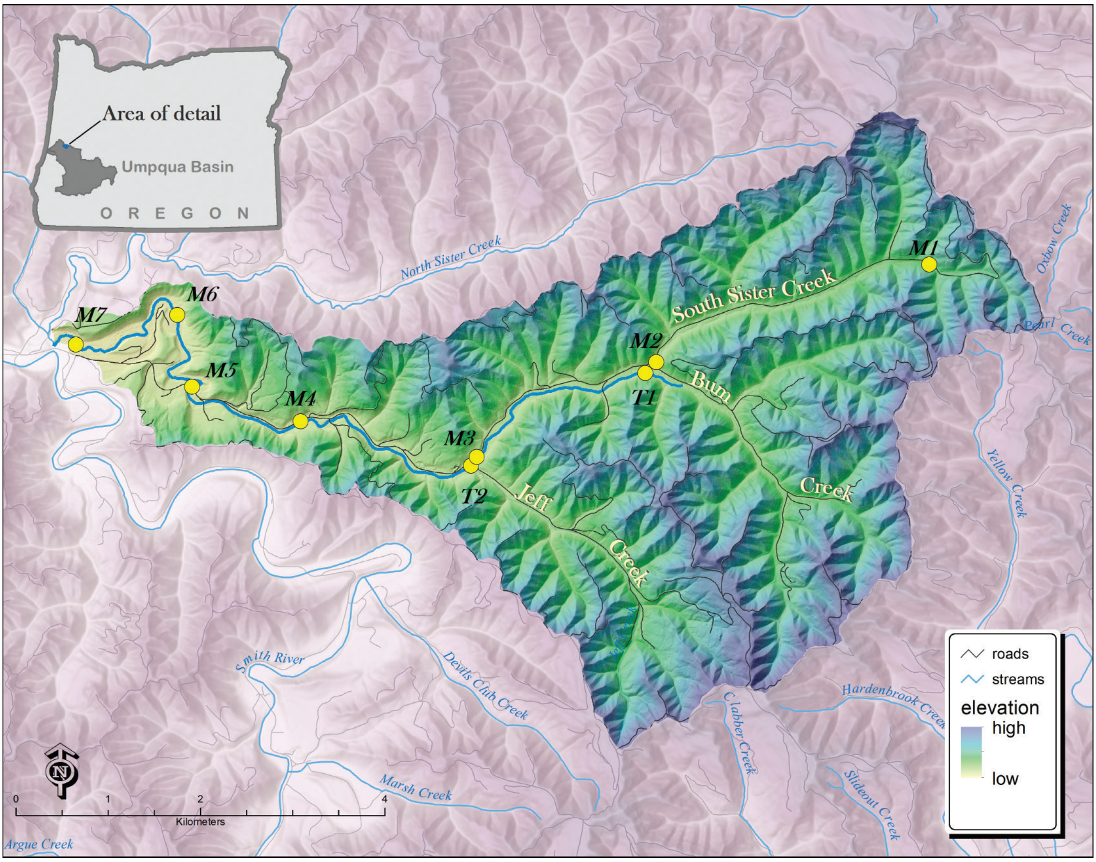

Figure 1. Map of South Sister Creek Watershed showing deployment sites for multi-year temperature-logging thermistors along the mainstem (M2, M3, M5, M7) of South Sister Creek, as well as additional deployment sites in summer 2013 on the mainstem (M1, M4, M6), and tributaries (T1 and T2). South Sister Creek extends downstream of the confluence with Bum and Jeff Creeks to the West Fork of the Smith River.

confining presence of South Sister Road," as the reason for the persistence of simplified habitat conditions, deeply incised channels, and lack of floodplain connectivity (BLM 1996).

Stream Enhancement Projects

Between 2007 and 2009, over 90 structures composed of boulders, large wood, and root wads were installed in South Sister Creek to promote habitat complexity and encourage deposition of gravel and cobble. Older structures (boulders, logs, and rootwads) had been installed in the 1990s in South Sister Creek, and above the confluence with Bum Creek in 2004 and 2006. Though incomplete, the available records suggest that the BLM and the Smith River Watershed Council (SRWC) placed more than fifteen thousand boulders and 400 logs in the South Sister catchment between 2007 and 2009. All logs were between one and a half (with rootwad) to twice (cut ends) the active channel width (which ranged between 15 and 35 m at the time of placement) and were a minimum of 0.55 m in diameter (ODF and ODFW 1995, OWEB 1999a).

Structure Georeferencing

In May and June of 2013, coordinates for every designed structure and natural log jam were collected using a hand-held global positioning system (GPS) while walking the length of the stream from its mouth, where South Sister Creek and North Sister Creek join before emptying into the

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Smith River, to the confluence with Bum Creek. Coordinate error (as indicated by the GPS unit) ranged between 4 and 12 m. Log jams and boulder fields could be readily identified as "enhancement structures" by the large size of logs with cut ends and boulders, presence of cable tethers, arrangement, and components. Although log jams are often defined as three pieces of wood touching, and counted on the basis of 1-m length (Wohl et al. 2010), in this structure survey, any two pieces of large wood over 3 m in length and 10 cm in diameter were considered a log jam (natural or placed). Stand-alone boulder fields were noted but not included in the overall structure count.

Quantifying the Spatial Distribution of Shade

A shade model was used to quantify the spatial pattern and total amount of shade reaching the stream from the headwaters to the mouth (Harewood 2015). The model is an ArcGIS (v. 10.1) model developed by the BLM to estimate "effective shade", defined as the proportion of direct solar radiation that is blocked during daylight hours by topography or vegetation. The model uses three LiDAR-derived raster layers (streams attributed with their underlying bare earth digital elevation model [DEM] elevation, a first return DEM, and Euclidean distance determining the desired buffer width measured outward from the centerline of the stream raster), and a solar data table including the solar azimuth, sun angle, and the percent of daily solar energy for each hour interval in a 24-hour cycle for a given day. From these inputs, the model calculated cumulative effective shade for each stream raster cell (1-m^2 resolution) for the buffer distance and day chosen. The data are displayed in the form of a float raster grid.

Stream Temperature Data Collection with Temperature Loggers

In 2006 and 2012, the BLM monitored longitudinal stream temperature between June and September using Hobo Water Temp Pro-V temperature-logging thermistors (hereafter referred to as loggers), which have a resolution of 0.02 °C at 25 °C and an accuracy of 0.21 °C between 0 °C and 50 °C. Loggers were placed in shaded pools deep enough that they would remain submerged throughout the summer, and collected temperature readings every 30 minutes. Four sites along the main channel of South Sister Creek (M2, M3, M5 and M7) were monitored from June to September in all three years of the study (2006, 2012, and 2013). In addition, we added three new 2013-only temperature logging sites along the main channel (Figure 1): M1—Upper (in headwaters), M4—at Structure 5, and M6—the Bend site, directly downstream of a 40-m long, unshaded bedrock riffle (Table 1). Loggers were also placed in the two major tributaries to South Sister Creek—Bum Creek (also called Burn Creek on some maps) and Jeff Creek—just above their confluences with South Sister Creek. Hereafter, we refer to the four loggers deployed continuously between June and September in 2006, 2012, and 2013 as "multi-year loggers", and those deployed in 2013 as "2013-only".

Prior to deployment and after retrieval, all temperature loggers were checked for accuracy following OWEB protocol (OWEB 1999b). All loggers passed accuracy checks within 0.2 °C and were audited monthly. Audits included measuring water level at placement, measuring depth of logger, checking batteries, and measuring stream temperature within 1 cm of the loggers with a National Institute of Standards and Technology (NIST) calibrated field thermometer to test for measurement agreement. For 25 of the 26 audit measurements, the agreement between the NIST-calibrated thermometer and the temperature loggers was within the 0.2 °C accuracy threshold of the loggers, and for the one exception, the subsequent temperature reading showed a difference of only 0.1 °C between the logger and the NIST field thermometer.

To obtain local data on air temperature in 2013 for comparison to the Goodwin Peak Remote Automatic Weather Station (RAWS) about 20 km northwest of the study watershed, we installed Hobo Tidbit2 temperature-logging thermistors in shaded locations at the M2 and M7 sites.

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TABLE 1. Attributes of sites at which temperature loggers were deployed along South Sister Creek (from headwaters to mouth) in study years 2006 (28 Jun 2006 to 17 Sep 2006), 2012 (14 Jun 2012 to 18 Sep 2012), and 2013 (19 Jun 2013 to 18 Sep 2013). Site codes with shaded cells indicated the four sites that were instrumented all three years. Sensors were anchored between 2 and 14 cm from bottom of pool (average 7 cm). Pool depths are those recorded 19 to 20 Aug 2013.

Site name	Site code	Shade (%)	Site type	Elevation (m)	Pool depth (cm)
Upper	M1	80	Pool by cut bank	220	22
Above Bum[1]	M2	80	Pool under logs	157	50
Above Jeff	M3	60-80	Pool by cut bank	134	36
Structure 5	M4	80	Pool under logs	116	20
Bridge	M5	60-80	Pool	108	32
Bend	M6	20-80	Riffle	95	56
Mouth	M7	0-80	Pool under logs	72	56

[1]Labeled as Burn Creek in some maps of the region; however, since BLM data refer to it as Bum Creek, we use Bum Creek here

Within-Reach Variability

To investigate temperature variation at finer spatial resolution within the stream, four sites were instrumented at the reach scale by placing multiple loggers within 80 m of the multi-year loggers during two 10-day periods in the summer of 2013. Additional sets of loggers were placed at the multi-year sites M2 and M3 as well as near 2013-only sites M4 and M6. The purpose of these deployments was to investigate within-reach temperature variation. These additional loggers were purposely placed in areas where temperatures might be expected to differ, such as off-channel pools, or shaded undercut banks, though placement was constrained by water level and ability to anchor sensors. Although streams in this region exhibit spatial heterogeneity over many different scales (Ebersole et al. 2003a, 2003b; Fullerton et al. 2015), it was beyond the scope of this study to characterize spatial heterogeneity for the entire stream; our goal here was to investigate the within-reach variability in stream temperature near the multi-year loggers.

Data collection occurred in two separate 10-day periods in the within-reach variability study, with temperatures recorded every 10 minutes. In the first 10-day period, (09 Aug 2013 to 18 Aug 2013) 5 temperature loggers were deployed within 50 m of the M2 multi-year logger, and 4 were placed within 50 m of the M4 logger. Locations of these additional loggers are described in Supplemental Table S1.

In the second 10-day period, (23 Aug 2013 to 01 Sep 2013), 3 loggers were placed within 60 m of the M3 logger, and 2 loggers were placed within 80 m of the M6 logger. Fewer loggers were placed at these sites because there were fewer locations in which water depths were adequate to fully cover the sensors of the additional temperature loggers. Locations in which these loggers were deployed are described in Supplemental Table S2. They were placed in locations where they could be anchored to the subsurface and in locations intended to capture different habitat types in the same stream segment (i.e., the portion of the reach between successive log jams) as the multi-year logger.

In order to measure vertical variation in stream temperature, the M2 site was additionally instrumented with four anchored wooden stakes equipped with iButton temperature loggers (Dallas Semiconductor, Dallas, Texas, USA), which were wrapped in 12.5-μm thick plastic wrap, secured with tape, and placed at 10, 20, and 30 cm above the base of the stake. The stakes were placed in the pool shared by the M2 multi-year logger to measure temperature gradients by depth. Four days of vertically stratified stream temperature data were collected at hourly intervals between 16 Aug 2013 and 19 Aug 2013. The pool was 31.7 m in length, dominated (about 80%) by fine sediment (the fine sediment class combined the categories of sand and silt, with a grain size of < 2 mm), had a maximum depth of 60 cm, wetted

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width of 5 m, and active channel width of 6.5 m. Stake A was placed adjacent to the M2 multi-year logger, Stake B was placed upstream of the logger, and Stakes C and D were placed downstream of the logger. More than 60% of the pool surface is shaded in August at this site (Harewood 2015).

Data Processing

Air temperature, precipitation, and solar radiation data for 2006, 2012, and 2013 were obtained from the University of Utah website (MesoWest 2020) for the Goodwin Peak RAWS, 16 km west and 11 km north of the study watershed. The 30-minute South Sister Creek stream and air temperature time series were converted to hourly time steps by averaging the point collected on the hour with the point collected at the half-hour. The Goodwin Peak RAWS solar radiation and air temperature data, as well as the hourly stream temperature data collected at multi-year sites for 2006, 2012, and 2013, were then filtered to isolate the high-frequency diel cycle from the low-frequency signal (e.g., trends in mean daily temperature) using a high-pass moving window filter (Fritts 1976).

Seven-day maximum stream temperatures were calculated and compared across sites and years. The 7-day maximum temperature (T_{max7}) was calculated by averaging maximum daily temperatures at each site for each period of record with a 7-day moving window. The maximum value from these smoothed data is defined as the 7-day maximum (T_{max7}).

To investigate whether in-stream structures influence the pattern of temperature extremes between years, we used a graphic analysis to compare T_{max7} at the M5 site (downstream of all structure installations) to T_{max7} for the M2 site (above the structure installations), plotting the data for M2 versus M5 in 2006, 2012, and 2013 (after Groom et al. 2011).

Statistical Analyses

Comparison of Stream Temperature and Air Temperature Data—Temperature data from the multi-year loggers were analyzed using a cross-correlation function to investigate whether temperature data patterns are consistent with increased hyporheic exchange following installation of in-stream structures. An increase in hyporheic exchange can lead to decreased temperature variability, with lower temperature maxima and higher minima compared to reaches without hyporheic exchange (Johnson 2004, Beechie et al. 2013). Hyporheic exchange can also produce lags in stream temperature response to warming from rising air temperatures and solar radiation (Arrigoni et al. 2008, Briggs et al. 2018).

The cross-correlation function (CCF) measures the relationship between two time series, where observations in the time series are correlated by lags (or leads). The strength of the correlation is described by the cross-correlation coefficient (r), which ranges from –1 to 1 (Jenkins and Watts 1968). Other studies have used the CCF to analyze streambed time series temperature data (Malard et al. 2001, Beach and Peterson 2013). We used the CCF to investigate the relationship between air temperature and stream temperature.

The filtered RAWS air temperature time series and filtered stream temperature at M7, M5, M3, and M2 for each year were used as the air temperature-stream temperature inputs to the CCF. The filtered data were used to focus on the short-term, diurnal patterns and remove the influence of longer-term temperature trends. The CCFs were computed for both an early summer (day of year [DOY] 182 to 213) and late summer (DOY 227 to 258) period, using a lag increment (k) of 1 hour, and a maximum number of lags (m) of 48 hours. All CCF calculations were carried out using the R programming language (R Core Team 2014) and the "ccf" command.

Analysis of the Variability of Stream Temperature at the Reach Scale—To assess spatial variability of stream temperature at the reach level, five metrics were calculated from each of the additional within-reach temperature loggers: daily mean (T_{mean}), daily minimum (T_{min}), daily maximum (T_{max}), and daily ranges (T_{range}). Kruskal-Wallis tests and Wilcoxon rank sum tests were used to test for a significant difference between temperature data from the short-term loggers placed within the reach for just 10 days, and corresponding data from the multi-year loggers for the same time period.

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Metrics for the "typical diel cycle" (Arrigoni et al. 2008) were used to compare temperature differences with depth from the iButton data. The typical diel cycle (TDC) is the mean temperature for each hour of the day across the sampling period. From this cycle, five metrics were used to compare the stream temperature: TDC max, hour of TDC max, TDC min, hour of TDC min, and the daily range between maximum and minimum temperatures.

Estimates of Stream Discharge

Because South Sister Creek is ungaged, discharge data were not available for this stream. To provide context for the stream temperature data, additional data for stream discharge on a nearby river were obtained from the US Geological Survey (USGS) gage for the Siuslaw River from 2006 to 2017.

Results

Structure Survey

Ninety-seven separate structures consisting of logs and large boulders were identified in South Sister Creek in the 10.8 km surveyed along South Sister Creek and the tributary Bum Creek (Table 2). All of the designed structures were located within about 6.8 km in the reaches upstream of the M5 site. Downstream of site M5, no designed structures were found, consistent with restoration installation records (BLM 2009).

We compared data collected on aquatic habitat in 2013 (Harewood 2015) to similar aquatic habitat data collected in a 1994 survey by the Oregon Department of Fish and Wildlife (ODFW 1995). The total area of aquatic habitat classified as pools on South Sister Creek between site M7 and the confluence with Bum Creek in 2013 was 42,483 m^2 (average pool depth 0.51 m), an 87% increase compared to 22,731 m^2 (average pool depth 0.57 m) in 1994.

Shade Analysis

Results of the shade analysis (Figure 2) show the calculated effective shade provided to the stream by trees in a buffer extending 500 m from the center of the stream. The location of the stream center line was based on the LiDAR-derived stream raster (1-m^2 resolution). Values are binned into 200-m segments, from 0 to 16 km upstream of the confluence of North and South Sister creeks. According to the shade model, more than 67% of South Sister is shaded for most of the day, with values of 90% or more effective shade. The lowest values of shade are concentrated near the mouth, downstream of the M5 site.

Temperature Results

Temperature patterns across sites and years—Stream temperature at South Sister Creek varied both longitudinally and over time. Stream temperatures showed longitudinal warming, with cooler temperatures at the upstream sites compared to temperatures at the downstream sites collected at the same time in all four years (Table 3, Figures 3 and 4). Air temperatures at the Goodwin Peak RAWS in all three study years are shown in Figure 4e for comparison with water temperatures at each monitoring site (Figures 4a to 4d).

For all periods of deployment, the M7 site (at the mouth of South Sister Creek, above the confluence with the Smith River) had the highest median for mean hourly stream temperatures (T_{mean}), maximum hourly stream temperatures (T_{max}), and minimum hourly stream temperatures (T_{min}), and the M1 sensor (in the headwaters) had the lowest median T_{mean}, T_{max}, and T_{min} temperatures (Table 4). The air temperatures shown in Figure 4e illustrate that 2006 was a warm year with record high temperatures in July, whereas 2012 was a relatively cool year, and 2013 was warmer than 2012 but cooler than 2006.

The record heat in 2006, pre-restoration, complicates the comparison of stream temperature pre- and post-restoration. Median values for the hourly stream temperatures at each site were highest for 2013 and lowest in 2012 (Figures 3 and 4), whereas maximum temperatures were highest at each site in 2006. Both stream temperature extremes and temperature ranges recorded were also highest for 2006.

In 2006, 2012, and 2013, T_{max7} exceeded 18 °C at one or more sites. The highest T_{max7} value for the study period was 25.1 °C at mouth (M7),

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TABLE 2. Number of designed and natural in-stream structures located in South Sister Creek. This table lists all designed structures (boulder weirs, log jams, cabled root wads and logs, and combination structures) as well as natural log jams per reach. Reaches are ordered from the lower to upper South Sister Creek. The reach between M3 and M2 temperature loggers had the highest density and number of structures, followed by the reach between the M4 and M3 temperature loggers.

		Structures	
Reach	Reach length (m)	Designed	Natural
1) Survey start to M7	479	0	1
2) M7 to M6	2,106	0	2
3) M6 to M5	1,474	0	2
4) M5 to M4	1,524	20	2
5) M4 to M3	2,514	30	2
6) M3 to M2	2,632	31	6
7) M2 to survey end	29	1	0
Total	10,758	82	15

and occurred in 2006. The lowest values of T_{max7} at each site were recorded in 2012, the study year in which air temperatures were coolest (Figure 5).

The median hourly air temperature from the Goodwin Peak RAWS, calculated over the deployment period in 2012, was 15.0 °C, whereas median hourly air temperatures in 2013 and 2006 were both 16.1 °C, more than a degree warmer. The summer of 2006 also had the highest air temperatures of the study years. The highest 7-day maximum air temperature for 2006 was 31.7 °C. The lowest 7-day maximum air temperature of 27.8 °C was recorded in 2012. Data from Goodwin Peak in 2013 were similar in range (8.1 to 30.6 °C), magnitude, and trends to the air temperature data we collected using Tidbit2 sensors at the M7 site in 2013 (Supplemental Figure S1). Air temperature data recorded using Tidbit2 sensors at the M1 site were cooler overall, with a narrower daily range (from 8.4 to 25.0 °C) than the Goodwin Peak air temperature data (Supplemental Figure S2).

Because South Sister Creek is ungaged, discharge data are not available for this stream. To provide context for the stream temperature data, we used data for stream discharge on the Siuslaw River from 2006 to 2017 (Figure 6). The data from the Siuslaw River gage near Mapleton, Oregon (USGS gage number 14307620) indicate that annual patterns in stream discharge in the region were similar among study years.

Diel Patterns in Solar Radiation, Air Temperature, and Stream Temperature

Streamflow shows a trend of decreasing discharge over summer each year, with sporadic peaks due to rainfall events. In addition to the time series shown in the previous section (Figure 4), the diel patterns of solar radiation, air temperature, and stream temperature provide information relevant to hyporheic exchange and groundwater input. The high-frequency diel cycles in stream temperature were preserved after the data were filtered using a high-pass filter for the four multi-year monitoring sites (Harewood 2015). Similarly, air temperature data and solar radiation data from Goodwin Peak filtered with a high-pass filter showed high-frequency diel cycles. The amplitude of the diel cycles in temperature decreased on cloudy days and at the end of the summer season. Coincident with precipitation events in mid July 2006, amplitudes of solar radiation dropped below ± 200 W m^{-2} (Supplemental Figure S3, see Harewood [2015] for corresponding data from 2012 and 2013). The decrease in solar radiation and onset of precipitation coincided with dampening in amplitude of the stream temperature.

Diel ranges in water temperature at Site M2 in all years had lower amplitude and became increasingly irregular beginning in August. This change coincided with decreases in water level measured at the West Fork Smith gage, and is consistent with what would be expected at baseflow when groundwater input makes up a higher proportion of streamflow.

Stream temperatures are correlated with regional air temperatures in early summer, but this correlation usually decreased in late summer (Table 4). In the early summer period of all three study years and sites, peak cross-correlation coefficients indicated a strong positive correlation between air and stream temperature ($r > 0.70$). In the late summer period (DOY 227 to 258), values for r

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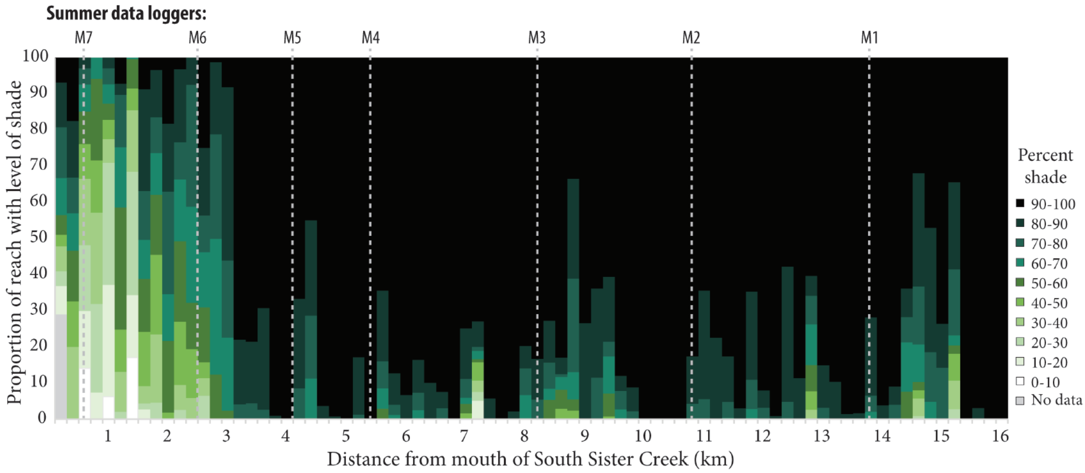

Figure 2. Results of shade analysis. Effective shade values range from 0 to 100%, where darker hues indicate higher shade values. The dashed lines indicate mainstem temperature logger locations. Low values are concentrated near the mouth, downstream of site M5. More than 67% of the creek from the mouth to 16 km upstream is shaded for most of the day, with values of 90% or more effective shade.

TABLE 3. Summary statistics for daily stream temperature data (daily maximum (T_{max}), daily minimum (T_{min}), daily mean (T_{mean}) and highest 7-day maximum temperatures (T_{max7}) from 28 Jun through 17 Sep for each study year.

Year and site	Site code	T_{max} (°C)	T_{min} (°C)	T_{mean} (°C)	T_{max7} (°C)
2006					
Mouth	M7	22.3	14.2	17.7	25.1
Bridge	M5	19.1	13.2	15.4	21.1
Above Jeff	M3	18.8	13.4	15.3	20.7
Above Bum	M2	17.5	11.9	14.0	18.7
2012					
Mouth	M7	18.4	13.1	16.2	19.8
Bridge	M5	16.8	12.3	14.7	18.0
Above Jeff	M3	16.6	12.0	14.5	17.7
Above Bum	M2	15.7	11.6	13.9	16.5
2013					
Mouth	M7	19.4	17.1	18.0	21.3
Bridge	M5	17.1	15.4	16.2	19.5
Above Jeff	M3	16.8	15.2	15.9	18.4
Above Bum	M2	15.8	14.4	15.0	17.0

generally decreased across years and sites but remained between 0.50 and 0.78, except at the M2 site during 2006 and 2013, when r decreased to 0.30 and 0.20, respectively. This compares to a value of r of > 0.70 during 2012. Lags ranged from 3 to 6 hours in 2006 and 2013, and from 4 to 5 hours in 2012. The M2 and M7 sites had higher lags in 2006 and 2013 than M3 and M5, but this relationship was reversed in 2012. In the late summer period, all but the M3 site in 2006 and the M5 site in 2006 and 2013 demonstrated lower r values. In late summer 2006 and 2013, cross-correlation coefficients for the M2 site were $r = 0.30$ (with a lag of 12), and $r = 0.20$ (with a lead of 20), respectively.

Variation Within Reach

The results of the within-reach variability study are shown in Table 5 and Table 6. Results of Kruskal-Wallis tests comparing medians of hourly time-series for additional loggers deployed in the same reach as the multi-year loggers indicated no significant difference between temperatures measured at M6 and M3 multi-year monitoring sites and the additional loggers placed in their reach in 2013 (Table 7). The temperature data from additional within-reach loggers deployed during a 10-day period in August at the M6 and

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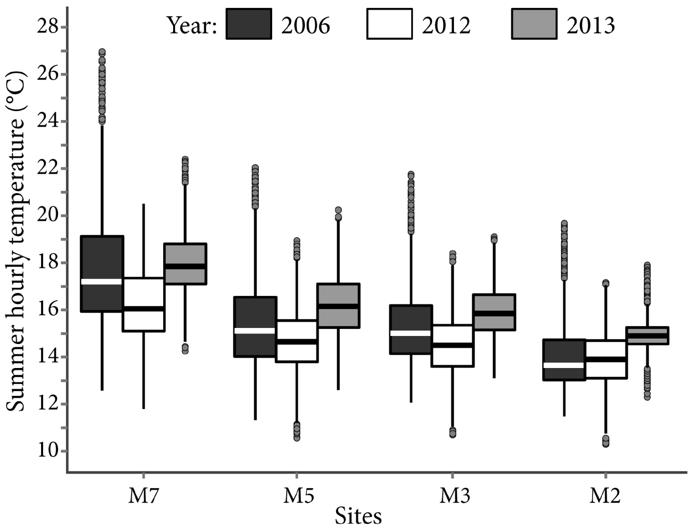

Figure 3. Boxplots of summer hourly stream temperature from all mainstem, multi-year study sites for 2006, 2012, and 2013. Although there is a consistent warming trend from the headwaters to the mouth, differences between median hourly temperatures at the M3 and M5 sites were less than 0.5 °C in each year.

M3 sites were not significantly different from each other or the primary logger at the site. This result emerged both from the lower variability of temperatures within sites near multi-year loggers M6 and M3, and because fewer supplementary loggers were deployed at these sites, owing to lack of locations for anchoring the loggers.

In contrast, Kruskal-Wallis tests indicated significant differences among temperatures measured in a 2-week interval by the addition loggers placed within the same reach as the M4 and M2 multi-year loggers (Table 7). These supplemental loggers recorded temperatures that were significantly different from the multi-year logger at M2 and M4.

Vertical Temperature Patterns at the M2 Site

We explored patterns of temperature variation with depth in the pool in which the M2 logger was deployed. Figure 7 shows the typical diel cycles recorded by the iButtons in the stakes that were placed in the same pool as the multi-year Pro-V2 temperature logger. For each stake, average temperature increased with distance from the bottom. The iButton loggers farthest (30 cm) from the bottom and closest to the surface demonstrated the strongest sinusoidal shape. The M2 multi-year logger (5 cm above the bottom) consistently had the lowest temperature. Temperatures became most similar during the coolest part of the diel cycle, from 8 to 10 am. Mean temperatures increased by an average of 0.8 °C between a point 10 cm from the creek bed to 30 cm from the creek bottom. Although these data on temperature variation with depth were collected from a single pool, they illustrate the benefit of in-stream structures that help create deeper pools in providing cool-water habitat.

Comparison of Temperatures Upstream and Downstream of Structures

We plotted T_{max7} at the M5 site (downstream of the structure installations) versus T_{max7} at the M2 site, upstream of the structure installations (Figure 8). The different symbols for each year are all increasingly shaded with increasing day of year. The pattern of strong correlation (r^2 = 0.99) between upstream and downstream temperatures in 2012, with very little hysteresis in the data during the September 2012 low flow period, is in contrast to the patterns shown for 2006 (r^2 =0.80) and 2013 (r^2 = 0.92). The early summer data for T_{max7} in 2006 and 2013 fall along the same trendline as the early summer 2012 data. However, in September 2006 (darkest shaded symbols), T_{max7} was much higher at the downstream site relative to the upstream site. The T_{max7} data for 2013 follow a similar pattern to the T_{max7} data in 2006, indicating that the in-stream structure treatment did not significantly alter the relationships in maximum stream temperature between these sites. Since both maximum air temperatures and maximum stream temperatures were higher in 2006 than in any other year, the cooler stream temperatures in 2012 and 2013 may simply reflect cooler air temperatures in those years. Although the lack of discharge data for South Sister Creek precludes an analysis of the influence of discharge on stream

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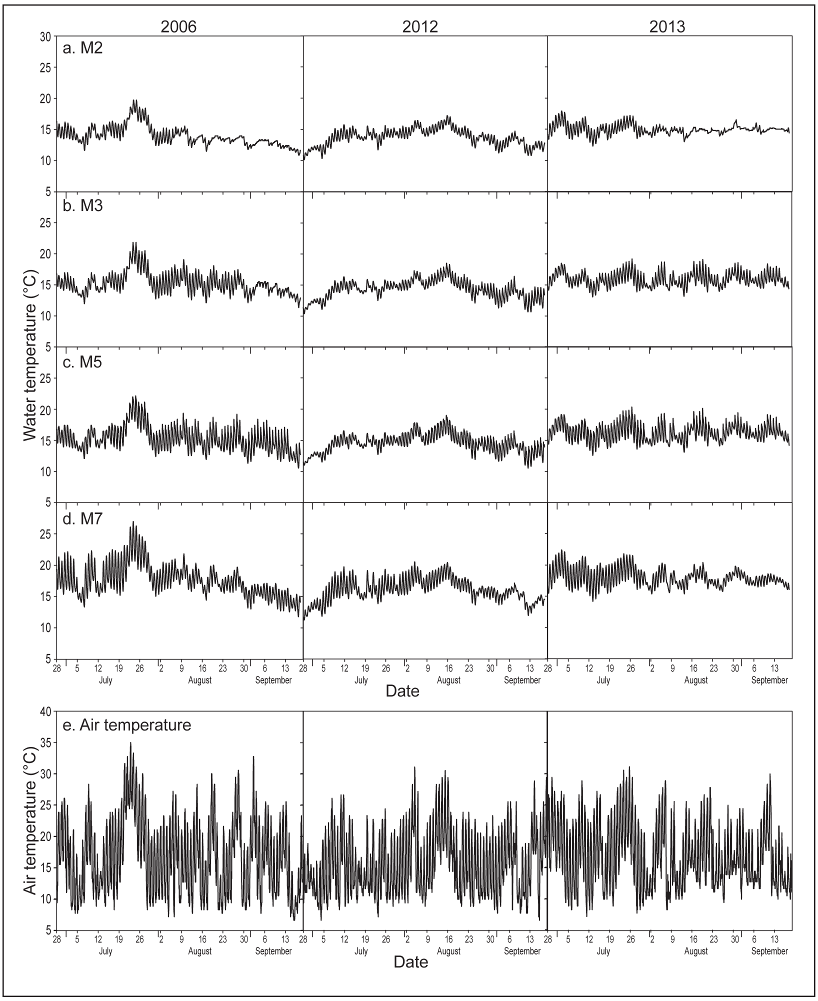

Figure 4. Time series of stream temperature (a–d) and air temperature (e) for study years 2006, 2012, and 2013. Stream temperatures are shown for the four multi-year logger sites instrumented in all three study years (a = M2, b = M3, c = M5, d = M7). Air temperatures (e) were recorded at Goodwin Peak Remote Automatic Weather Station (RAWS) in 2006, 2012, and 2013.

temperature, data from the Siuslaw River do not indicate exceptionally high or low streamflows in the summer months of the study years.

Discussion

Overview

This study examined patterns in stream temperature along a 10-km length of South Sister Creek as well as reach scale patterns that may have been influenced by in-stream restoration projects occurring between 2007 and 2011. Our data suggest that installation of structures in the stream has not resulted in significantly cooler average stream temperatures at monitoring sites within South Sister Creek. Comparison of the data from habitat surveys in 1994 and 2013 indicates that the area in pool habitat has increased in that time period, providing greater habitat complexity within the stream and more cool-water habitat in the form of deeper pools (Figure 7). These trends are associated with a decreased frequency and magnitude of extreme temperatures in the deeper pools. Although more research is needed to better understand the relationship between the presence of in-stream structures and geomorphic response of this stream, it appears that in some reaches, the presence of structures may have increased habitat complexity, especially pool habitat. Visual field observations noted the presence of pools associated with structures installed in glides and homogenous flow reaches.

Longer monitoring with an increased number of temperature loggers is needed to better understand the temperature trends in this stream. In addition, the installation of gages to monitor discharge over time is important to assist in the interpretation of these temperature data.

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TABLE 4. Values of cross-correlation coefficient (*r*) and lag times (k) from comparison of stream temperature data from multi-year mainstem loggers (M2, M3, M5 and M7) and air temperature data from Goodwin Peak Remote Automatic Weather Station (RAWS) for early summer (DOY 182 to 213) and late summer (DOY 227 to 258).

	DOY 182 to 213		DOY 227 to 258	
Site	*r*	k	*r*	k
M2 2006	0.76	6	0.30	12
M2 2012	0.81	5	0.73	7
M2 2013	0.78	6	0.20	0
M3 2006	0.74	3	0.55	4
M3 2012	0.76	5	0.74	3
M3 2013	0.76	3	0.78	4
M5 2006	0.70	3	0.72	4
M5 2012	0.76	4	0.67	3
M5 2013	0.67	3	0.68	3
M7 2006	0.80	5	0.74	3
M7 2012	0.84	4	0.55	6
M7 2013	0.84	5	0.68	5

Trends in Warming from Upstream to Downstream Sites

In all three years of data collection, stream temperatures at the multi-year logger sites in South Sister Creek showed a trend of longitudinal warming. Lowest values of T_{max7} were recorded at the upstream site (M2) compared to downstream sites across all years. The magnitude of the overall mean increase in stream temperature from the upstream site M2 to the downstream site at the mouth (M7), a distance of about 10 km, ranged from 2.3 °C (warming of 0.22 °C per km) in the coolest year (2012) to 3.4 °C (warming of 0.36 °C per km) in the warmest year (2006). Stream temperatures recorded at the M7 site were consistently warmer than temperatures recorded at the same time at the M2 site. The daily mean stream temperatures for the four multi-year sites on South Sister Creek (Table 3) would be in the 75th quartile relative to the temperatures reported from 2002 to 2004 for streams studied by Dent et al. (2008) and Groom et al. (2011). Air temperatures reported for their sites in 2002 to 2004 ranged from 19.0 to 19.9 °C.

The pattern of longitudinal warming observed at South Sister Creek, Oregon is consistent with patterns observed in other Oregon coastal basins. Dent et al. (2008) found that 63% of Oregon Coast Range streams displayed at least a 2 °C increase per 300 m in comparisons of 7-day maximum stream temperatures. In contrast, 26% showed a cooling pattern, and 11% showed no significant change. In our study, only the reaches between M5 and M7 (all years) and between M2 and M3 in 2006 warmed at the rate of 2 °C per 300 m. South Sister Creek has substantially less shade in these lower reaches, especially downstream of the M5 site. In addition to increased exposure to solar radiation downstream of the M5 site, higher proportions of bedrock substrate may contribute to higher maximum temperatures in these reaches. This would be consistent with Johnson's (2004) finding that maximum temperatures were higher in reaches with bedrock substrate than in reaches with alluvial substrate.

Do Monitoring Results Indicate Cooler Stream Temperatures Post-Restoration?

Our first research question asked whether monitoring results indicated cooler stream temperatures post-restoration. Differences in weather between years and limited monitoring pre-restoration complicate the answer to this question. Median stream temperature values were highest in 2013 and coolest in 2012 for all four of the multi-year summer-term logger sites (Figure 4). The daily mean temperature at the M2 site was 15.0 °C in 2013 compared to 14.0 °C in 2006 and 13.9 °C in 2012 (Table 3). However, 2006 had much higher temperature extremes than 2012 or 2013. For example, between 28 Jun and 18 Sep in 2006, hourly temperatures at the M7 site ranged from 11.8 to 27 °C, compared to a range of 14.2 to 22.4 °C in 2013 and 11.2 to 20.5 °C in 2012. Seven-day maximum temperatures (T_{max7}) were higher in 2006 than in 2013 (Figure 5), although stream temperatures in 2012 were cooler for all metrics than both 2006 and 2013, with the lowest values of T_{max7} as well as lowest maximum, minimum, mean, and median stream temperatures.

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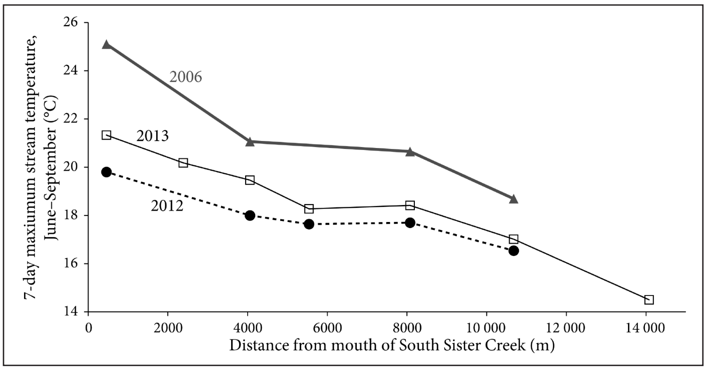

Figure 5. Plot of 7-day maximum temperature (T_{max7}) for instrumented sites (downstream site M7 at left to upstream site M1 at the farthest right) in 2006 (triangles), 2012 (open squares), and 2013 (filled circles). Values of T_{max7} in 2006 exceeded 18 °C, the criterion for rearing temperature that led to South Sister Creek's 303(d) listing in 2006. Site M7 is near the mouth of South Sister Creek, about 0.5 km above the confluence with the West Fork of the Smith River. Sites M6, M5, M4, M3, M2 and M1 are located upstream of the confluence at distances of 2.4, 4.1, 5.6, 8.1, 10.7 and 13.7 km, respectively. Data shown are T_{max7} data for individual loggers at each site.

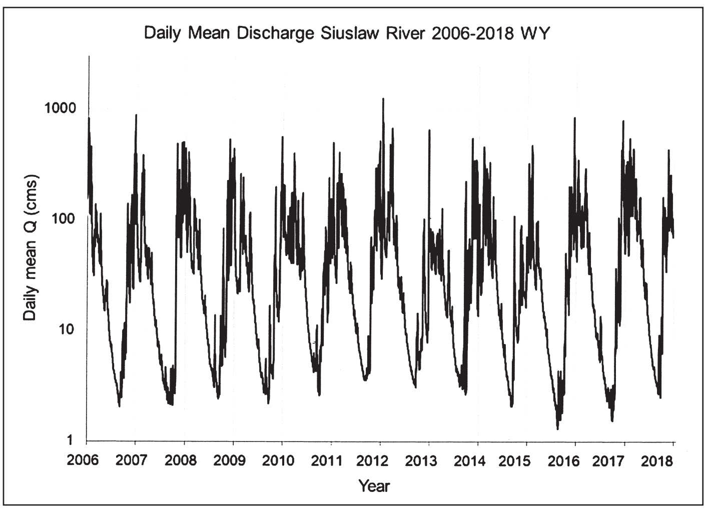

Figure 6. Stream discharge in cubic meters per second (CMS) for Siuslaw River gage 14307620 (closest USGS gage in the region with continuous discharge data for all study years).

In early summer of 2013, stream temperatures were relatively high compared to previous years. Values of T_{max7} for the first week of record at the M2 site were 13.8 °C in 2006, 12.0 °C in 2012, and 15.7 °C in 2013. Over the course of the summer, however, the highest values of T_{max7} were recorded for 2006, during a record July heat wave (Figures 5, 8).

Are Temperature Patterns Consistent with Increased Hyporheic Flow?

Cross-correlations between stream temperature and air temperature were used to investigate whether stream temperature patterns were consistent with those expected under conditions of increased of hyporheic flow. If hyporheic exchange increased after in-stream structure placement, one would expect to see increased time lags at sites downstream of in-stream structures in post-restoration years. One would also expect a decrease in the diel range of stream temperature relative to diel air temperature, leading to lower correlations between stream and air temperature. Peak cross-correlation values ($r > 0.70$) indicated a strong correlation between air and stream temperature in early summer (DOY 182 to 213) across multi-year sites and years (Harewood 2015). However, in the late summer period (DOY 227 to 258), the strength of the correlation generally decreased at all years and in all sites, but r remained between 0.50 and 0.70, except at the M2 site, where r values decreased to 0.30 and 0.20 during 2006 and 2013. The observed pattern is consistent with either increased groundwater influence or increased hyporheic flows at the M2 site, influence that increases as water level decreases late in the summer. The stream temperature patterns observed in this study can help identify segments of the stream with lower ranges of variability and higher lag times between air and water temperature (e.g., M2) which could become the focus of further research on hyporheic flow.

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TABLE 5. Values of T_{mean}, T_{max}, T_{min}, and T_{range} at each mainstem logger (M2 to M7), at tributaries (T1—Bum Creek and T2—Jeff Creek), and at short-term loggers indicated by asterisk (M4-A to M4-D and M2-A to M2-E) between 09 Aug 2013 and 18 Aug 2013.

	Median			
Site	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	T_{range} (°C)
M7	17.8	18.7	17.0	1.9
M6	16.5	18.2	15.2	3.0
M5	16.0	17.6	14.9	3.3
M4	15.8	16.8	15.2	2.1
M4-A*	15.9	16.8	15.3	1.9
M4-B*	15.9	16.9	15.3	2.0
M4-C*	15.0	16.1	14.5	1.8
M4-D*	15.9	17.0	15.3	2.2
M3	15.7	17.1	14.9	2.4
M2	14.8	15.3	14.5	0.7
M2-A*	15.4	16.2	14.7	1.7
M2-B*	15.5	16.3	14.7	2.0
M2-C*	14.1	14.5	13.7	0.9
M2-D*	15.0	15.7	14.3	1.2
M2-E*	15.4	16.4	14.6	1.7
M1	13.3	13.7	13.0	0.8
T2—Jeff Creek	15.2	16.4	14.2	1.9
T1—Bum Creek	15.2	16.0	14.6	1.3
Overall median	15.4	16.4	14.7	1.7
Overall standard deviation	1.2	1.4	1.1	0.9

Diel water temperature cycles in South Sister Creek varied with solar radiation and air temperature (Supplemental Figure S3), results consistent with those from other studies (Sinokrot et al. 1996, Mohseni and Stefan 1999). Stream segments above M5 are highly shaded (usually > 80% shade). Presence of bedrock was also positively correlated with higher stream temperatures, and with a higher daily range in stream temperature. Although mean and maximum daily stream temperatures increased with distance downstream in all years, diel ranges were greatest at the M5 site (below a bedrock-dominated reach) in all three study years. The loggers at the M5 and M6 sites were in bedrock pools. All three mainstem sites with high diel temperature ranges were located downstream of bedrock riffles. These findings are similar to those of Dent et al. (2008), in which proportion of bedrock substrate in headwater streams of the Oregon Coast Range was positively correlated with T_{max7}.

Temperature Variability at Reach Scale

Habitat complexity, particularly in the upstream reaches of South Sister Creek, were associated with greater heterogeneity of stream temperatures within the stream reach. For example, locations within the reach of multi-year logger M2 displayed the greatest variation in stream temperature of the four short-term sites, with temperature differences of about 1.0 °C between the M2 logger and the short-term loggers deployed around logger M2 at the same time (Table 7). At M5 and M3, both areas without in-stream structures and with limited complexity, short-term loggers showed no significant differences in stream temperature (Table 7). The M4 and M2 sites both had in-stream structures and demonstrated significant differences in median temperatures, with the greatest within-reach variation in stream temperature measured at the M2 site. The M2 site also displayed the greatest habitat complexity and thermal heterogeneity. In sum, the comparison of stream temperatures collected by additional sensors deployed for 10 days within 50 m of the M4 and M2 temperature loggers using Kruskal-Wallis tests showed statistically significant differences among data from sensors placed in different areas within these reaches, suggesting that more loggers at both the M2 and M4 site would be required in order to capture the full range of variability in these reaches.

Data from sets of iButtons placed vertically on stakes located within the same pool as the M2 logger indicated that mean water temperatures and diel ranges in temperature decreased with depth. All of the summer-term loggers are placed in deeper locations (often in pools ranging from 0.6 to 1 m

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TABLE 6. Values of T_{mean}, T_{max}, T_{min}, and T_{range} at each mainstem logger (M2 to M7), at tributaries (T1—Bum Creek and T2—Jeff Creek), and for short-term loggers indicated by asterisk (M3-A to M3-C and M6-A to M6-B) deployed for 10-day periods between 23 Aug 2013 and 01 Sep 2013.

Logger site	Median			
	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	T_{range} (°C)
M7	17.9	18.7	17.1	1.5
M6	16.8	18.3	15.5	2.5
M6-B*	17.0	18.6	15.5	2.5
M6-A*	16.7	18.3	15.5	2.4
M5	16.5	17.9	15.3	2.2
M4	15.8	16.4	15.4	1.2
M3	16.1	17.5	15.1	2.0
M3-A*	16.1	17.6	15.1	2.0
M3-B*	16.1	17.6	15.1	2.0
M3-C*	16.0	17.2	15.2	1.5
M2	14.8	15.1	14.8	0.6
M1	13.9	14.2	13.6	0.7
T2—Jeff Creek	15.5	16.4	14.6	1.8
T1—Bum Creek	15.3	16.0	14.9	1.2
Overall median	15.9	17.9	15.1	1.7
Overall standard deviation	1.2	1.5	1.0	0.8

TABLE 7. Values of Kruskal-Wallis statistic from comparison of temperature measurements between multi-year mainstem loggers (M2, M3, M4, and M6) and the additional loggers (whose temperature data are listed in Tables 5 and 6) placed within the same reach in 2013, for each set of multi-year and short-term loggers.

Site	χ^2	df	Number of measurements	*P*
M2	437	5	1,460	2.2×10^{-16}
M3	1.36	4	960	0.72
M4	133	4	1,200	2.2×10^{-16}
M6	3.16	2	720	0.21

deep) within the stream in order to ensure that they will remain submerged throughout the season. The thermal stratification we observed was consistent with results from other studies. Ebersole and others (2003a,b) found vertical stratification of 3 to 12 °C in cold patches with depths that ranged from 0.06 to 1.01 m. Similarly, Tate et al. (2007) measured temperatures up to 7.6 °C cooler and consistently more constant at the bottom of pools compared to pool surface waters. The tendency to place monitoring loggers in deeper pools likely leads to over-representation of locations in which stream temperature is cooler and less variable. Although placement of sets of loggers in a range of environments within the stream could give a more accurate representation of the range of stream temperature conditions at the reach scale, more frequent audits would be required to ensure that the sensors remained under water.

Implications for Monitoring Stream Temperature Pre- and Post-Restoration

Despite recognition of the need for monitoring of restoration projects, the lack of monitoring reported (Palmer et al. 2007, Katz et al. 2007) by the National River Restoration Science Synthesis (NRRSS) working group persists. The NRRSS studied project records for over 37,000 projects in the United States through 2005, and concluded that: "…practitioners were highly dedicated individuals with a genuine desire to improve ecological conditions. However, they were often constrained by what project sponsors provided funds to do; funds were generally not provided for ecological premonitoring and rarely for ecological postmonitoring. Any monitoring that was funded was most often limited to visual surveys of the site, photographs, or channel cross-sections." A global review of the literature (Roni et al. 2008) to assess the effectiveness of five major categories of stream rehabilitation, including the installation of in-stream structures, found that nearly half of all articles (163 of the 345 papers identified) reported monitoring effectiveness of in-stream structures. Most of those studies were from the western United States, and duration, scale, and metrics used to assess effectiveness varied. The

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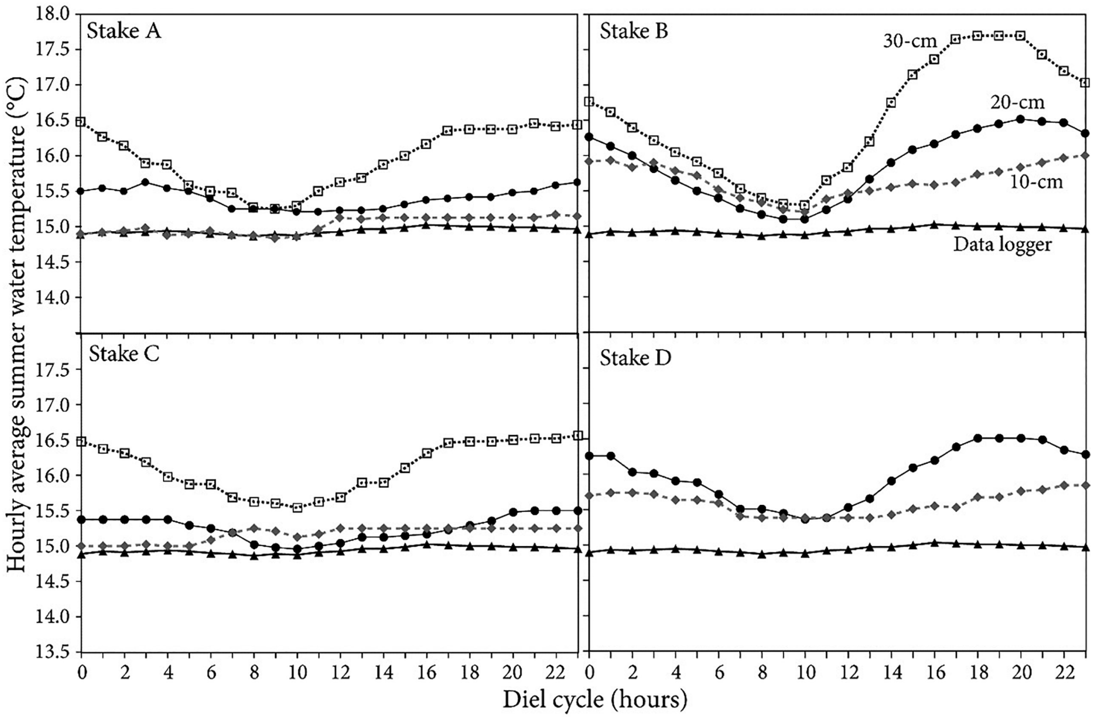

Figure 7. Temperature variation with depth (distance from pool bottom) averaged for four days in August 2013 for the M2 logger placed 5 cm from the bottom of the pool, and iButtons at depths 10 cm, 20 cm, and 30 cm from the bottom of the pool, for four pools ranging in depth from 25 cm to 60 cm.

average duration of these studies was 3.4 years, and not all included pre-monitoring.

The restoration projects on South Sister Creek are among the 30% of all projects in the Pacific Northwest with some temperature monitoring (Bash and Ryan 2002, Katz et al. 2007), and among a minority of such projects that include a year of pre-restoration monitoring and regular audits of the temperature loggers with NIST thermometers throughout the summer. Even with this level of attention to methods, and the dedication to accurate monitoring shown by the local BLM hydrologist, monitoring has been constrained by low levels of funding. The present study was conducted in summer 2013 with a budget of $2,500 provided by the BLM, matched by a National Science Foundation Science, Technology, Engineering, and Mathematics Scholarship to the second author. Funding for organizations conducting restoration should include funds specifically targeted to pre- and post-restoration monitoring. Improved monitoring is necessary to inform adaptive management, as well as for planning for and adaptation to impacts of climate change (Perry et al. 2015). This also means that funding for restoration projects should extend for longer periods of time to allow sufficient time for multiple years of pre-restoration monitoring, the restoration itself, and post-restoration monitoring.

Conclusions

Although our results do not indicate a significant cooling of stream temperature overall in South Sister Creek due to placement of in-stream structures, they do indicate an increase in habitat heterogeneity and the creation of pool habitat which can provide refugia for fish in the late summer. This increase in pool habitat may be the greatest initial benefit from the restoration activities, whereas sediment accumulation sufficient to promote greater hyporheic exchange in the stream system may take longer to occur.

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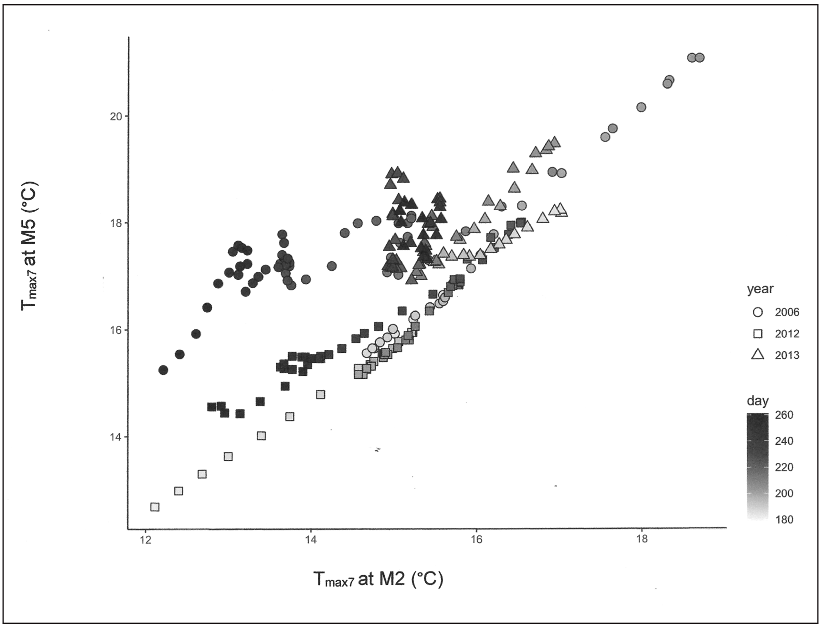

Figure 8. Plots of 7-day maximum temperature (T_{max7}) at the M2 (upstream) site versus T_{max7} at the M5 (downstream) site for years 2006, 2012, and 2013. The different symbols for each year are all increasingly shaded with increasing day of year. While stream temperature at M5 was always correlated with upstream temperature at site M2, the strongest correlation occurred in 2012 (r^2 =0.99), with lower correlation between sites in 2006 (r^2 =0.80) and in 2013 (r^2 =0.92).

Our work extended and increased the number of sampling sites used in ongoing monitoring of South Sister Creek by the BLM. Although patterns in stream temperature across the 2006 to 2013 period were consistent with those expected if hyporheic exchange increased in the stream post-treatment, data sets that are limited to one year pre-treatment and two years post-treatment are not sufficient to demonstrate long-term temperature trends, or to determine whether or not increased hyporheic flow resulting from in-stream restoration is the cause of the observed changes in temperature patterns. Our results can provide a baseline for subsequent investigations to test whether the stream temperature patterns reported here are consistent over time. It has also helped to identify locations for further study (such as the M2 site) in which hyporheic flow or groundwater input may be important.

Because 7-day maximum temperatures above the total maximum daily load (commonly referred to as TMDL) criteria for trout and salmon rearing habitat (> 18 °C) persist along much of South Sister Creek in late summer, we recommend additional investment in monitoring and stream gaging to assess the influence of restoration on stream temperature and guide further efforts. Continuous streamflow data would help parameterize a physical temperature model, as would data from monitoring wells installed in locations which our data indicate may be receiving groundwater input or hyporheic exchange.

In-stream structures are not typically associated with net cooling except where they enhance gravel deposition. Although habitat surveys conducted by Harewood (2015) noted an increase in pool habitat relative to surveys conducted by ODFW in 1994, the proportion of bedrock substrate decreased only slightly in treatment reaches, indicating that the installation of these structures has not yet been effective in increasing the accumulation of gravel and cobble in the stream. The lack of recruitment of gravel and cobble in the stream was not surprising, given that surveys conducted by the BLM in 1968 and 1969 following the Oxbow fire reported increased fine sediment in the stream and adjacent banks. Additional research is needed that focuses on aquatic habitat and the sediment sources to the stream.

The work presented here can help guide future efforts in stream temperature monitoring to better capture the range of spatial and temporal variation, even for organizations limited by time and financial resources. At a reach scale, sites with more structures displayed greater habitat

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complexity and spatial variability in temperature than bedrock-dominated reaches with simpler geomorphology. Variability between and within sites should be considered when locating instrumentation, with location of deployment depending on the questions of interest. Finally, our study underscores that longer periods of pre-treatment monitoring are required to provide an adequate comparison of pre- and post-treatment conditions. For example, in this study, the only pre-treatment monitoring year, 2006, was a relatively warm year and did not represent the normal range of pre-treatment conditions. Pre-treatment monitoring should extend for multiple years, in order to capture some of the year-to-year variability and allow more statistical power for comparisons of pre- and post-treatment conditions.

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