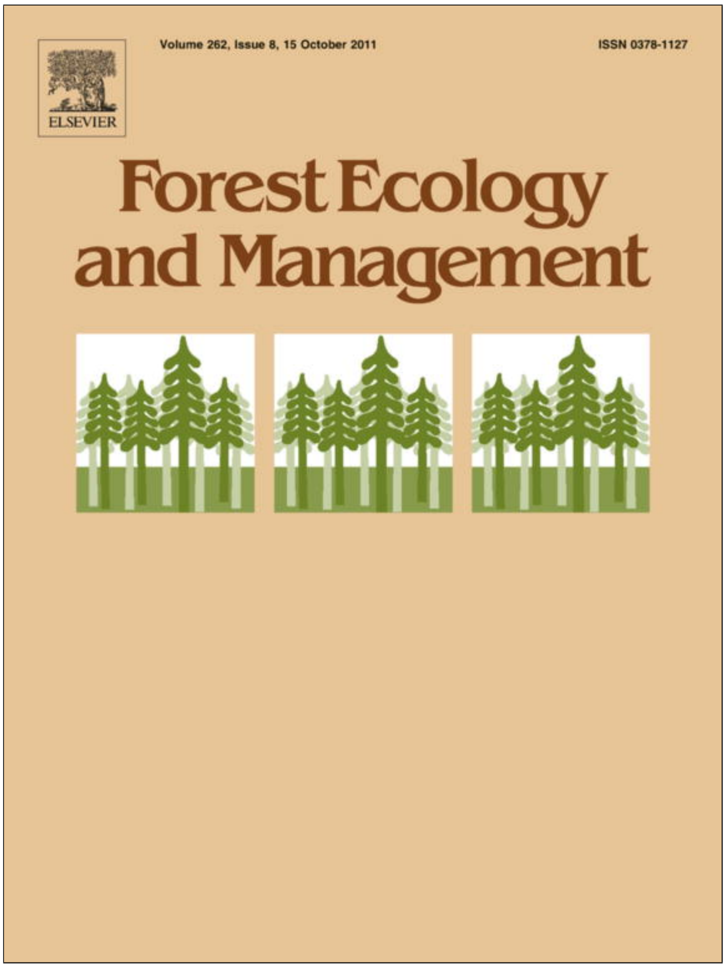
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Forest Ecology and Management 262 (2011) 1618–1629

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Response of western Oregon (USA) stream temperatures to contemporary forest management

Jeremiah D. Groom [a,*], Liz Dent [b], Lisa J. Madsen [c], Jennifer Fleuret [d]

[a] Department of Forest Engineering, Resources, and Management, Oregon State University, 204 Peavy Hall, Corvallis, OR 97331, USA
[b] Oregon Department of Forestry, 2600 State St., Salem, OR 97310, USA
[c] Department of Statistics, Oregon State University, 44 Kidder Hall, Corvallis, OR 97331, USA
[d] 923 W Pine St., Rawlins, WY 82301, USA

ARTICLE INFO

Article history:
Received 3 May 2011
Received in revised form 6 July 2011
Accepted 8 July 2011
Available online 3 August 2011

Keywords:
Riparian buffer
Stream temperature
Mixed-effects
Shade

ABSTRACT

A replicated before–after-control-impact study was used to test effectiveness of Oregon's (USA) riparian protection measures at minimizing increases in summer stream temperature associated with timber harvest. Sites were located on private and state forest land. Practices on private forests require riparian management areas around fish-bearing streams; state forest's prescriptions are similar but wider. Overall we found no change in maximum temperatures for state forest streams while private sites increased pre-harvest to post-harvest on average by 0.7 °C with an observed range of response from −0.9 to 2.5 °C. The observed increases are less than changes observed with historic management practices. The observed changes in stream temperature were most strongly correlated with shade levels measured before and after harvest. Treatment reach length, stream gradient, and changes in the upstream reach stream temperature were additionally useful in explaining treatment reach temperature change. Our models indicated that maximum, mean, minimum, and diel fluctuations in summer stream temperature increased with a reduction in shade, longer treatment reaches, and low gradient. Shade was best predicted by riparian basal area and tree height. Findings suggest that riparian protection measures that maintain higher shade such as the state forests were more likely to maintain stream temperatures similar to control conditions.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

The Oregon Coast Range supports several cold-water fisheries (e.g. salmon, steelhead, cutthroat) which are important to the region's economy, culture, and recreational activities. These fish are thermally adapted to specific water temperatures for various life stages such as egg and smolt survival, spawning, and adult migration (Richter and Kolmes, 2005). Because forest management can influence stream temperature regimes it is important to evaluate the effectiveness of contemporary riparian management strategies to protect stream temperature.

Stream temperature patterns are the result of several energy transfer processes and reflect both the seasonal change in net solar radiation and the spatial and temporal changes in other energy transfer processes including evaporation, convection, conduction, and advection (Brown, 1969; Caissie, 2006; Johnson, 2004). The magnitude and direction of these energy transfer processes are influenced by atmospheric conditions (solar radiation, air temperature, wind speed, cloud cover and relative humidity), basin level physical factors such as surrounding topography, surface and groundwater flow, and streamside vegetation (Poole and Berman, 2001; Sinokrot and Stefan, 1993). The amount of shade provided by streamside vegetation is perhaps the most important single variable affecting summertime stream temperatures in forested environments (Brown, 1969; Johnson and Jones, 2000; Danehy et al., 2005).

Historic forest management along streams often resulted in dramatic reductions in shade and associated increases in stream temperature (Brown and Krygier, 1970; Levno and Rothacher, 1967; Harris, 1977; Holtby and Newcombe, 1982; Feller, 1981; Johnson and Jones, 2000; Moore et al., 2005). Moore et al. (2005) summarize findings from several historic and contemporary studies in the rain-dominated region of the Pacific Northwest. Reported changes in maximum stream temperature for sites harvested without a riparian buffer ranged from 1.4 to 11.6 °C. The changes were

Abbreviations: AZ, azimuth; BAPH, basal area per hectare; ChannelBD, channel blowdown; CR, crown ratio; CT, control reach temperature change standardized by reach length; EL, elevation; FPA, Forest Practices Act; GR, gradient; HS, harvest status; ODEQ, Oregon Department of Environmental Quality; OW, owner; PlotBD, plot blowdown; PP, private site post-harvest; RMA, riparian management area; SH, shade; TL, treatment reach length; TPH, trees per hectare; WS, watershed area.

* Corresponding author. Tel.: +1 541 737 1502; fax: +1 541 737 4316.
E-mail addresses: jeremy.groom@oregonstate.edu, jeremygroom@gmail.com (J.D. Groom), ldent@odf.state.or.us (L. Dent), madsenl@onid.orst.edu (L.J. Madsen), jenniferfleuret@gmail.com (J. Fleuret).

0378-1127/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2011.07.012

Author's personal copy

considered to be a result of increased solar radiation at a time when harvesting did not require riparian buffers, slopes were broadcast burned to the edge of the stream, and equipment operation occurred in stream channels.

Varying levels of effectiveness for contemporary riparian buffers have been reported in the literature. Moore et al. (2005) reported a range of 2.5–5.0 °C for streams with riparian buffers in the Pacific Northwest. The variability in stream temperature responses may be due in part to different management practices. Within the reported literature sites differ according to harvest strategy (clearcut harvest or different levels of thinning) and levels of riparian vegetation retention (Moore et al., 2005). The variability in temperature responses may additionally be a function of multiple biological and physical site factors that affect the energy transfer processes. For example, while removal of vegetation can decrease shade it can also result in an increase in summer low flows. This may result in an increase in cool groundwater that would moderate the effects of a shade reduction on stream temperature (Moore and Wondzell, 2005). Stream velocity and depth also influence the sensitivity of the stream to change (Brown, 1969). Danehy et al. (2005), Isaak et al. (2010), and Isaak and Hubert (2001) found elevation to serve as a predictor of stream temperature. Gomi et al. (2006) posited that valley azimuth may have influenced the effectiveness of leave-tree buffers at intercepting incoming solar radiation. Geomorphic features such as channel sediment deposits (Johnson, 2004) or channel reaches scoured by debris flows (Levno and Rothacher, 1967) can also influence the sensitivity of the stream to changes in temperature changes.

Determining the effects of contemporary harvest practices on stream temperature involves detecting relatively small changes in stream temperature within a wide range of background variability. Background variability is a function of several factors including basin size [Caissie, 2006; Lewis et al., 1999], microclimatic and geologic processes (Brosofske et al., 1997; Hawkins et al., 1997; Kasahara and Wondzell, 2003), and annual and spatial hydrological variability (Poole and Berman, 2001; Quinn and Wright-Stow, 2008). As such, longitudinal patterns can be highly variable in small streams (Dent et al., 2008; Torgerson et al., 1999). Study and analysis designs must therefore be able to separate this inherent variability from potential harvest effects.

Groom et al. (2011) evaluated changes in stream temperature following harvest in the Oregon Coast Range. Their study design was developed to account for aforementioned spatial and temporal variability. They reported a 40% increase in the probability that stream temperatures would exceed 0.3 °C following timber harvest conducted according to Oregon harvest regulations for small and medium fish-bearing streams. The frequency of temperature increases did not surpass background levels for sites harvested according to state forest standards. While their analysis allowed them to address a state water quality standard it hindered their ability to provide estimates of the actual magnitude of change or to evaluate potential drivers of stream temperature change (e.g., treatment reach length, shade, riparian and stream characteristics).

Quantification of the magnitude of stream temperature change allows for the comparison of results to other studies and historical effects of harvest, and provides insight into background variability. Also, the development of changes in riparian policy requires an understanding of how management-controlled factors affect shade and temperature changes. Therefore the objectives of this analysis are to:

1. Identify site physical and vegetative factors, including shade, that relate to stream temperature change.
2. Determine the magnitude of stream temperature change that results from timber harvest.
3. Quantify riparian characteristics that predict shade retention after harvesting.

We expand our assessment of stream temperature beyond the water quality standard-focused weekly maximum temperatures reported by Groom et al. (2011) and examine daily maximum, minimum, and mean temperatures as well as diurnal fluctuation, in order to better capture the spectrum of temperature changes following harvest. The implications of findings for this study likely extend to other regions with similar physical and biological characteristics, stream temperature concerns, cold-water fisheries, and prescriptive riparian zone protections such as Idaho, Alaska, British Columbia, Washington, and California.

2. Methods

2.1. Study location and design

This study was conducted at 33 sites in the Oregon Coast Range (see Fig. 1 in Dent et al., 2008). Sites were situated along first- to third-order streams on 18 private and 15 state forest sites dominated by Douglas fir (*Pseudotsuga menzeisii*) and red alder (*Alnus rubra*). Forest stands were 50–70 years old and were fire- or harvest-regenerated. Openings were dominated by shrubs such as vine maple (*Acer circinatum*), stink currant (*Ribes bracteosum*), salmonberry (*Rubris spectabilis*), and devil's club (*Oplopanax horridus*).

The study design rendered a probabilistic sampling approach impractical due to the specificity of site inclusion criteria and the resulting scarcity of sites. The criteria included an ability to collect at least 2 years of pre-treatment and 5 years of post-treatment data at every site, minimum treatment reach lengths of 300 m, and assurance that the upstream "control" reaches would remain unharvested for the duration of the study. Streams needed to qualify under the Oregon Forest Practices Act (FPA) as "Small" or "Medium" (mean annual streamflow <57 or between 57 and 283 L/s, respectively), and streams needed to be free of recent impacts from debris torrents and active beaver ponds. We obtained sites by requesting that industrial private and state forest managers in the Oregon Coast Range provide ODF with a list of stream reaches that met the criteria and would be harvested no sooner than 2004. An initial list of 130 stream reaches was reduced to 36 (three more were subsequently dropped due to changes in harvest plans) that met study design constraints. Assuming selected sites were geographically representative (all available sites that met selection criteria were included in the study), inferential scope of study results pertain to

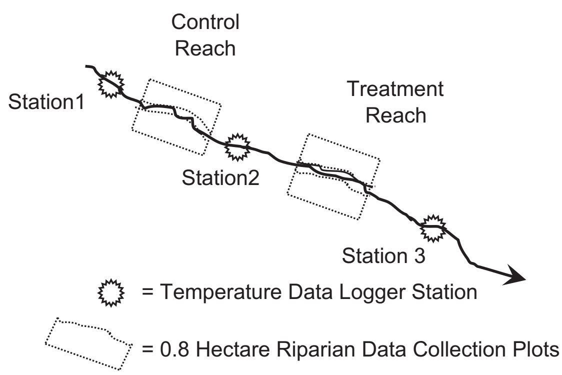


Fig. 1. Schematic of a stream reach (from Dent et al. 2008). Data loggers were placed starting upstream at Stations 1, 2, and 3. The upstream Control reach laid between Stations 1 and 2, the treatment reach between Stations 2 and 3. Riparian Data Collection Plots were located on either side of the stream in the Treatment and Control reaches; in this study we only used riparian data from the Treatment reach plots.

Author's personal copy

first- to third-order streams within the Coast Range, on 50–70-year-old non-federal forestlands primarily managed for timber production that lack recent debris torrent or beaver disturbance. While there was an initial attempt to exclude sites with beaver activity, a beaver dam ponded 220 m of the 1.16 km treatment reach for site 7801 during the first and second post-harvest years.

A site's control reach was located immediately upstream of its treatment reach (Fig. 1). The control reaches were continuously forested to a perpendicular slope distance of at least 60 m from the average annual high water level. Reach lengths varied from 137 m to 1,829 m with means of 276 m and 684 m for the control and treatment reaches, respectively.

2.2. Treatments

Forest Practices Act On Private Sites: Eighteen sites were established on private forest streams. Sites were harvested following contemporary FPA standards which require riparian buffers along fish-bearing streams to protect stream temperature, provide future large wood for streams, and retain other ecological services (Oregon Department of Forestry, 2007). Under the FPA, Coast Range RMAs are 15 and 21 m wide around small and medium fish-bearing streams, respectively. Both small and medium streams may not be harvested within a 6 m zone immediately adjacent to the stream. Harvesting is allowed in the remaining RMA to a minimum basal area of 10.0 (small streams) and 22.9 (medium streams) m^2/ha.

Oregon State Forest Management Plan (FMP) on State Sites: Land administered directly by Oregon Department of Forestry (state forests) is managed under the FMP for multiple resource objectives including timber production (e.g., recreation, wildlife) and require riparian protections that exceed FPA minimum values. State RMAs are 52 m wide for all fish-bearing streams, with an 8-m no cut zone. Limited harvest is allowed within 30 m of the stream only to create mature forest conditions. Harvest operations within this zone must maintain 124 trees per hectare and a 25% Stand Density Index (Oregon Department of Forestry, 2001). If mature forest conditions exist or will develop in a timely manner without management, then no harvest is allowed within 30 m of the stream. Additional tree retentions of 25–111 conifer trees and snags/hectare are required between 30 and 52 m.

2.3. Data collection

Optic Stowaway Temp and HOBO Water Temp Pro data loggers (Onset Computer Corporation, Bourne, Massachusetts) were annually deployed at three stations within each site beginning in 2002 or 2003 (Fig. 1). Station 1 was located at the upstream end of the control reach, Station 2 was located at the downstream end of the control reach and the upstream end of the treatment reach (i.e. shared logger) and Station 3 was situated at the downstream end of the treatment reach. Temperature loggers were deployed in shaded locations where stream flow was relatively constant at a reliable summer depth and within a well-mixed water column. Logger accuracy was checked prior to installation, in the field, and following retrieval with National Institute for Standards and Technology-calibrated digital thermometers according to Oregon Watershed Enhancement Board (1999) stream temperature protocol. Although both types of loggers are listed as ±0.2 °C accuracy, we found that for over 500 pre- and post- deployment assessments, in only two instances did loggers register errors of >0.1 °C. Daily temperatures that exhibited increases in diel fluctuation and increases and decreases in daily maximum and minimum temperatures that were not reflected in other probes during the same year or at the same location during other years were excluded from the analysis.

Channel data were collected at 60 m intervals within each reach. Data included wetted width, bankfull width, thalweg depth, and stream gradient according to the protocol described by Kaufmann and Robison (1998). Stream shade was quantified at each 60 m interval using a self-leveling fisheye lens digital camera (Valverde and Silvertown, 1997). Shade values were measured once pre-harvest and once post-harvest. Fish-eye photographs were taken in the middle of the stream, 1 m above the water level, and oriented due north. Photographs at this height may slightly underestimate stream shading due to shading from the banks, lower-growing vegetation, and channel wood (Davies-Colley and Quinn, 1998). An effort was made to take photos when the sun would not be in the picture (e.g. overcast conditions, when the sun was below the topographic horizon) and under dry conditions. Shade values were calculated from the photographs using HemiView™ 2.1 software (Delta-T Devices, Cambridge, UK) as one minus the June 30 Global Site Factor (1 -GSF). The GSF is the proportion of both direct and diffuse energy under a plant canopy relative to the available direct and diffuse energy for the given site's latitude/longitude. Shade and gradient values were averaged for each reach.

Vegetation data were collected in four 152 by 52 m plots on either side of a study stream in the treatment and control reach (Fig. 1). Plots were centered midway along each reach and altered in layout to accommodate stream nonlinearity. Vegetation plot data describe understory, overstory, downed wood, blowdown, and snag characteristics. The original purpose of including extensive vegetation plot data collection was to assess large wood recruitment, shade, and riparian structure following timber harvest. For this analysis we use a portion of the available riparian structure data (e.g. blow down, tree heights, basal area) that both influence stream temperature and relate to timber management. Within each plot all living trees with a diameter at breast height (DBH, or diameter at 1.4 m above ground level) >14 cm were tallied by species and the distance from those trees to the bankfull edge of the stream recorded. Height and live crown ratio were additionally measured for 20% of the trees. Data were collected in all four vegetation plots per site pre-harvest and re-measured in treatment plot or plots (if one or both stream sides were harvested, respectively) post-harvest. Blowdown was quantified in all plots post-harvest.

We determined stream elevation (elevation at the Station 3 logger), treatment reach azimuth, and watershed area from a geographic information system (GIS). We determined study site elevation from examining GPS-determined logger locations against 10-m digital elevation models (USGS National Mapping Program; overall absolute vertical root mean square error of 2.44 m). Azimuth was calculated using GPS locations of treatment reach upstream and downstream loggers. Since an east-west valley azimuth is expected to deliver the most solar radiation to a stream (Gomi et al., 2006; Sridhar et al., 2004), we "folded" (rendered equivalent) the azimuth north to south by subtracting 180 degrees (Hawkins et al., 1997; Bartholow, 1989), then folded the azimuth east to west by subtracting an additional 90 degrees. The result represents a 0–90° deviation from either east or west. Watershed area was calculated using the Spatial Analyst extension's Watershed tool for ArcGIS 9.3.1 (Earth Systems Research Institute, Redlands, CA). The tool relies on the same 10-m DEM as was used for elevation. Watershed area was calculated at the downstream end of the treatment reach (Station 3).

2.4. Analysis

We limited this analysis to include all pre-harvest data and data from the first and second post-harvest years. This decision was made due to a staggered harvest schedule and some prolonged

Author's personal copy

pre-harvest periods resulting in incomplete five-year post-harvest data. Data collection included hourly stream temperature data (collected annually between July 1 and September 15) and both channel data (for a complete list see Dent et al., 2008) and riparian vegetation data (overstory and understory) during the first years pre-harvest and post-harvest.

We examined our stream temperature, riparian vegetation, and channel data with two distinct analyses. We constructed one analysis to functionally understand processes influencing stream temperature, which addressed the first two of our three objectives. This analysis involved four measures of temperature as separate dependent variables and stream, shade, and riparian characteristics as independent variables. We developed several models for this analysis to determine a reasonable fit for the data as well as to obtain magnitude of effects estimates. To address the third objective, we conducted another analysis that examined several riparian vegetation metrics to determine which best related to observed stream shade values post-harvest. For both analyses we plotted and assessed potential explanatory variables by examining Pearson's correlations and variance inflation factors (VIF) to determine degrees of multicollinearity. We retained all temperature and shade analysis variables as VIF scores were all <10, indicating a lack of multicollinearity (temperature maximum = 1.76, shade maximum = 2.50; Neter et al., 1996). Prior to analysis we centered all independent variables by subtracting the variable mean from all values. We assessed dependent variables (change in treatment reach temperature for the four temperature analyses and Shade for the shade analysis) graphically to determine whether transformations appeared appropriate.

2.4.1. Analysis I: stream temperature

We summarized hourly stream temperature data to provide daily maximum, mean, minimum, and fluctuation (maximum-minimum) values for each data logger. Our analysis objectives 1 and 2 concerned detecting changes in stream temperature due to site factors including harvest. We therefore defined the response variable as the difference between treatment reach Stations 2 and 3. To reduce analysis complexity we computed the average of this difference over a forty day period for each year (July 23 to August 15). This represents the time frame when we had the most functional loggers recording temperatures during a central portion of the summer months when maximum temperatures are observed in the Oregon Coast Range. Averaging of temperature differences removed the variability associated with temperature differences from shorter time periods, such as single days. Temperature changes observed in this study therefore reflect prolonged alterations in stream conditions. The stream temperature analyses utilize the averaged differences in daily maximum, mean, minimum, and fluctuation values as separate dependent variables and we refer to these metrics as Maximum, Mean, Minimum, and Diel Fluctuation.

Independent variables used for modeling temperature included treatment reach length (TL), average treatment reach shade (SH), elevation (EL), average treatment reach gradient (GR), treatment reach valley degree deviation from east or west (AZ), change in control reach temperature standardized by control reach length (CT; ControlMax, ControlMean, ControlMin, ControlFluc), and watershed area calculated at Station 3 (WS). We also included state and private ownership (OW), the harvest status or whether a temperature measurement occurred during a pre-harvest or post-harvest year (HS), or a variable that indicated temperature data were from private forest during post-harvest (PP; included due to its importance in Groom et al., 2011). Except for shade and harvest status, all other explanatory variable values were static over all years. The variables TL and CT were included in all temperature models considered except an intercept model (Intercept) and one that only included CT (Upstream, Table 1).

Our modeling approach involved first selecting an appropriate random-effects model structure, followed by an evaluation of potential explanatory models of interest. We modeled the temperature data using mixed-effects linear regression (Pinheiro and Bates 2000). We selected this technique due to a concern of potential data non-independence within sites and within specific years. To determine the appropriate random effects structure for each of the temperature analyses we created an over-fit "beyond optimal" linear model (BO; Zuur et al., 2009) that additively included all independent variables and accounted for as much of the fixed-effects variation as possible. We then compared different random-effects structures that used this fixed-effects model structure. The random effect structures differed according to data groupings and

Table 1
Comparisons of different fixed-effects parameterizations for temperature models with similarly structured random effects. A set of model results are presented for each of the treatment reach changes in daily Maximum, Mean, Minimum, and Fluctuation values. Results are sorted by Maximum ΔAIC values. Rank indicates relative AIC order within a type of temperature analysis; a rank of 1 indicates the lowest AIC score. The symbol ro indicates model weight. All models include an intercept; linear combinations of independent varibles are provided[a]. See text for a definition of variables.

Model name	Independent variables[a]	Maximum			Mean			Minimum			Diel fluctuation		
		Rank	ΔAIC	ω	Rank	ΔAIC	ω	Rank	ΔAIC	ω	Rank	ΔAIC	ω
Grad_Shade	GR, SH, TL, CT	1	0.00	0.40	1	0	0.43	2	0.4	0.20	3	0.7	0.18
ShadeGradWS	GR, SH, WS, TL, CT	2	0.40	0.33	2	0.8	0.29	5	1.6	0.11	4	1.7	0.11
StreamShade	SH, TL, CT	3	2.70	0.10	3	1.9	0.17	1	0	0.24	6	1.8	0.11
FullStream	GR, SH, WS, AZ, TL, CT	4	3.40	0.07	5	4.5	0.05	7	3.1	0.05	5	1.7	0.11
El_Shade	EL, SH, TL, CT	5	3.70	0.06	4	3.8	0.06	4	1.2	0.13	2	0.3	0.22
BO	GR, SH, WS, AZ, HS, OW, TL, CT, EL	6	5.30	0.03	6	7.5	0.01	12	7.1	0.01	1	0	0.26
Harvest_PXLength	PP, PP×TL, TL, CT	7	25.70	0.00	7	20	0.00	6	3	0.05	7	18.4	0.00
Harvest_Private	PP, TL, CT	8	33.60	0.00	8	23.1	0.00	3	1	0.15	8	29.4	0.00
Harvest	HS, TL, CT	9	57.50	0.00	9	38.6	0.00	10	6.5	0.01	9	49	0.00
Harvest_S_P	HS, OW, TL, CT	10	59.40	0.00	10	39.3	0.00	11	6.9	0.01	10	50.9	0.00
Upstream_TRlength	TL, CT	11	71.70	0.00	11	51.6	0.00	8	5.8	0.01	13	63.4	0.00
GradWS	GR, WS, TL, CT	12	72.30	0.00	12	52.8	0.00	14	8.1	0.00	17	66	0.00
Phys	GR, WS, EL, TL, CT	13	72.90	0.00	15	54.8	0.00	16	9	0.00	15	64.9	0.00
StreamAzimuth	AZ, TL, CT	14	73.60	0.00	13	52.9	0.00	9	6.3	0.01	16	65.4	0.00
Upstream	CT	15	73.90	0.00	17	56.3	0.00	17	15.6	0.00	12	61.9	0.00
AzimuthGradWS	AZ, GR, WS, TL, CT	16	74.00	0.00	14	53.7	0.00	15	8.2	0.00	18	68	0.00
El_Azimuth	EL, AZ, TL, CT	17	74.30	0.00	16	54.9	0.00	13	7.5	0.01	14	64.2	0.00
Intercept	–	18	74.50	0.00	18	61.5	0.00	18	16.3	0.00	11	60.5	0.00

[a] Gradient = GR, shade = SH, treatment length = TL, control temperature change = CT, watershed area = WS, valley azimuth = AZ, elevation = EL, owner = OW, Harvest Status = HS, private site post-harvest = PP, PP × treatment length = PP×TL.

Author's personal copy

Table 2
Annual weather and stream flow conditions at a representative weather station[a] and stream gage[b]. Air temperature data are the mean of daily maximum temperatures across the 40-day study period. Spring Precipitation is cumulative precipitation from 1 January to the beginning of the study period. Study Precipitation is cumulative precipitation during study period. Stream Flow is the average daily flow averaged over the study period.

Year	2002	2003	2004	2005	2006	2007	2008
Air temperature (°C)	24.4	26.0	25.8	26.5	25.1	21.8	24.2
Spring precipitation (cm)	126.9	134.5	139.9	139.9	129.8	93.9	112.5
Study precipitation (cm)	0.38	0.30	0.30	0.30	0.08	5.56	6.15
Stream flow (L/s)	53.1	44.3	72.5	79.7	51.4	52.5	72.8

[a] Rye Mountain Remote Area Weather Station. Lat: 45.2172; long: −123.5358.
[b] US Geological Survey gage 14303200 near Blaine, OR. Lat: 45.1928; long: 123.3243.

random-effects parameterization. The models were fit using Maximum Likelihood estimation to enable comparison of model AIC values (Zuur et al., 2009). Random effects structures included a generalized least squares model (no grouping), a random intercept model grouped by site, another by year (2002 through 2008), and a third by a cross of site and year. We examined grouping data by year to potentially account for inevitable interannual differences in air temperature, stream flow, and precipitation (Table 2). Three additional models included a random intercept and slope for control temperature change and grouped data respectively by site, year, and a cross of site and year. The best-supported (smallest AIC) Beyond-Optimal model for all four temperature metrics grouped data by site and fit random effects parameters for intercept and control reach temperature change (respectively the control change in Maximum, Minimum, Mean, or Diel Fluctuation).

Once we selected an appropriate random-effects parameterization we altered the fixed effects and fit a suite of 18 explanatory models (Table 1). The models were constructed a priori to account for variation in stream temperature according to the stream's in-channel, riparian, and/or shade characteristics (Objective 1, Table 1 Maximum Rank models 1 through 5, 12 through 14, 16, and 17). To obtain temperature change magnitude estimates as a function of timber harvest we included models that specified harvest status (pre- or post-harvest), ownership, or a combination (Objective 2, Maximum Rank models 7 through 10). We included two more models, BO, and Intercept, to serve as overfitting and underfitting extremes. We included models Upstream and Upstream_TR-length to verify that CT and TL were indeed assisting model fits. Models for comparison were fit using Maximum Likelihood estimation to enable comparison of model AIC values; best-performing models were re-fit using Restricted Maximum Likelihood to reduce bias in parameter estimates (Zuur et al., 2009). We compared model weights (ω) to determine the probability that a model or subset of models represented or included the best model of the set (Burnham and Anderson, 2002).

2.4.2. Analysis II: shade

Shade analysis variables from the vegetation plots included trees per hectare (TPH), tree height (Height), live crown ratio (CR), vegetation plot blowdown (PlotBD), and basal area per hectare (BAPH). These variables were calculated by using vegetation plot data from the edge of the bank to a perpendicular distance of 30 m, a distance at which tree canopies have likely ceased to influence stream shade during daily periods of the greatest radiation intensity (mean measured tree height = 25.7 m). We obtained site values for these variables by calculating mean values for the two treatment reach plots. In instances where only a single side of the treatment reach was harvested we calculated the mean TPH, BAPH, and CR values from the harvested side's post-harvest values and the unharvested side's pre-harvest values. Height and CR values were obtained from pre-harvest data. Non-vegetation plot variables included the number of riparian banks harvested (Nsides), buffer width (BuffWidth), and channel blowdown (ChannelBD). We quantified BuffWidth as the perpendicular distance from the stream bank to the first stump encountered within 10 m of the observer, measured every 60 m along the treatment reach. ChannelBD represented a tally of treatment reach within- or above-channel blowdown pieces >15 cm diameter.

Shade data were logit transformed due to observed skewness. We performed a linear regression analysis of shade data (n = 33) and compared small-sample AIC values (AICc, Hurvich and Tsai, 1989) to determine relative model performance among 8 *a priori* models (Table 3). Models were comprised of variable combinations we believed could potentially describe variations in observed post-harvest site shade levels. Allen and Dent (2001) found that riparian basal area and live crown ratio served as useful shade predictor variables for east-west flowing streams in the Oregon Coast range. DeWalle's (2010) riparian shade model found combinations of specific tree height, density, and basal area maximized stream shade. We therefore created several models that contained combinations of BAPH, CR, TPH, and Height. At a more coarse level of analysis, we anticipated that buffer width and the number of stream sides harvested might serve as reasonable predictors of shade (model BuffWidth). An additional model anticipated that shade values would be predicted by the quantity of blowdown both across the channel and within vegetation plots (model Blowdown).

2.4.3. Analysis assessment

For both the stream temperature and shade analyses we examined q–q normal and residual plots to verify that the best-performing models met their respective required statistical assumptions. Linear models assume a linear relationship between independent and dependent variables, independence of errors, a constant variance and normality of errors. Linear mixed effects models additionally assume (1) within-group errors are independent and identically, normally, distributed with a mean of zero and a variance of σ^2, and are independent of random effects; and (2) random effects are normally distributed, with a mean equal to zero and a homogeneous random effects covariance matrix (Pinheiro and Bates, 2000). Visual assessment of residual and q–q plots indicated that the assumptions of within-group normality were plausible and within-group residuals were symmetrical around zero. Within-group variances did not appear equal (not surprisingly, given that the maximum number of points per site was six with a mean of four (Pinheiro

Table 3
AIC ranking for seven of the eight Shade models. Only the R^2 value is presented for the model Blowdown as the parameter BD_Channel had 31 observations. For all other variables n = 33.

Model	Variables	k	ΔAICc	ω	R^2
BasalXHeight	BAPH, Height, BAPH*Height	4	0.00	0.99	0.69
BasalHeight	BAPH, Height	3	10.70	0.00	0.50
BasalCR	BAPH, CR	2	15.08	0.00	0.43
BasalArea	BAPH	4	16.10	0.00	0.33
BufferWidth	NSides, BuffWidth, Nsides*BuffWidth	4	16.91	0.00	0.33
TreesXBasal	TPH, BAPH, TPH*BAPH	3	17.89	0.00	0.46
Intercept	–	1	25.03	0.00	0.00
Blowdown	PlotBD, ChannelBD	–	–	–	0.06

Author's personal copy

Table 4
Fixed- and random-effect parameter values for four linear mixed-effects models and their assocaited temperature response variables. Model StreamShade lacks a parameter for gradient and model El_Shade replaces gradient with the parameter elevation. Parameters for treatment length and gradient are expressed as change in temperature per 1 km of distance or elevation. Observations = 119, Groups (Sites) = 33.

Response Model	Maximum temperature Grad_Shade				Mean temperature Grad_Shade				Minimum temperature StreamShade				Diel fluctuation[b] El_Shade			
Fixed[a]	DF	Value	SE	*p*	DF	Value	SE	*p*	DF	Value	SE	*p*	DF	Value	SE	*p*
Intercept	29.1	0.494	0.125	0.001	28.1	0.282	0.080	0.001	28.6	0.183	0.059	0.004	30.2	0.238	0.094	0.017
CT	21.5	−1.232	0.459	0.014	21.7	−1.230	0.345	0.002	22.8	−0.518	0.310	0.109	23.2	−0.783	0.583	0.193
TL	28.2	0.800	0.304	0.014	27.6	0.638	0.194	0.003	27.8	0.549	0.144	0.001	31.5	0.627	0.279	0.031
SH	94.5	−5.866	0.572	0.000	97.5	−3.050	0.371	0.000	101.0	−0.881	0.314	0.006	99.6	−4.698	0.503	0.000
GR[b]	30.3	−0.076	0.036	0.040	29.6	−0.043	0.023	0.067	–	–	–	–	31.1	−0.104	0.057	0.079
Random			Std.Dev				Std.Dev				Std.Dev				Std.Dev	
Intercept			0.441				0.181				0.095				0.241	
ControlTemp			3.564				1.134				0.975				6.175	
Residual			0.079				0.040				0.031				0.060	

[a] Control reach temperature change = CT, gradient = GR, shade = SH, treatment length = TL.
[b] For Diel Fluctuation the variable for GR is replaced by elevation (EL). Other parameters in the model are the same.

and Bates, 2000); at the same time no site appeared to behave as an obvious outlier. Plots of observed vs. fitted values indicated that the linear models agreed with observed values. For daily temperature Maximum, Mean, and Diel Fluctuation, three values from two sites appeared to be outliers, while we found one potential outlier for Minimum temperatures.

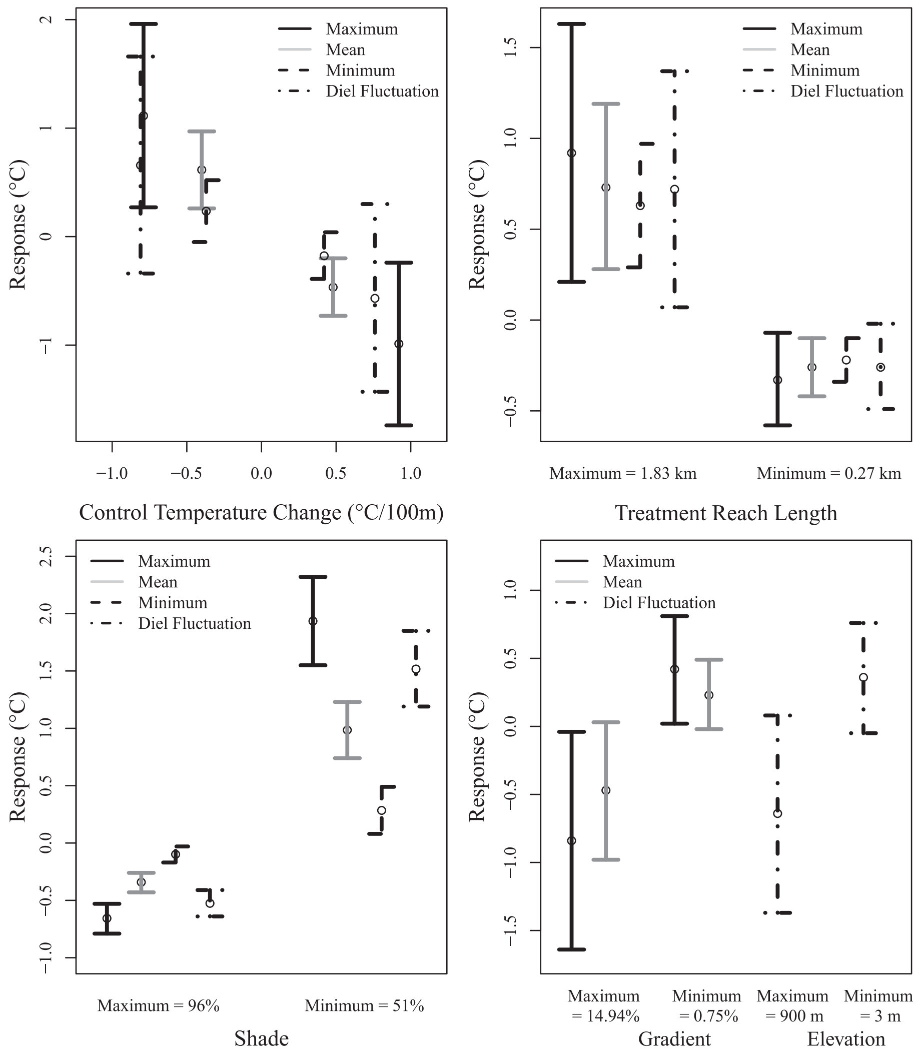


Fig. 2. Predicted temperature response for Maximum, Mean, Minimum, and Diel Fluctuation metrics at the observed extreme values of single explanatory variables and at the mean of all other variables. Explanatory variables presented appear in the models Grad_Shade and El_Shade. The El_Shade model, best supported by the Diel Fluctuation temperature metric, differs from Grad_Shade in that it replaces the Gradient parameter with Elevation. Influences of Gradient and Elevation extremes for those models appear in the lower right figure. Circles in each figure represent point estimates with 95% confidence intervals. In the upper left graph control temperature change represents change over 100 m.

Author's personal copy

For the second assumption, normal q–q plots for the intercept and Control random effects provided no indication of non-normality. Normal q–q plots of Maximum, Mean, and Minimum intercept values revealed two potential outliers out of 33; Diel Fluctuation exhibited three. For the CT random effect Maximum, Minimum, and Diel Fluctuation plots we found one outlier apiece and zero for Mean. Homogeneity of random effects by group was difficult to assess due to the general paucity of data for each site.

3. Results

3.1. Analysis I: stream temperature

Our ranking of models explaining observed temperature changes indicated that shade was critical, with all other variables marginally improving model fit (Table 1). For change in daily temperature Maximum, Mean, and Fluctuation the best-supported six models are those that included SH; models that lacked shade exhibited a substantial drop in explanatory power (increase in ΔAIC by >13). We found little support for non-shade models as the cumulative model weight for models that included shade was effectively 1.0. For changes in the Maximum and Mean treatment reach temperatures the model with shade and gradient (Grad_Shade) and gradient, shade, and watershed area (ShadeGradWS) performed best. The lowest-AIC model for Diel Fluctuation was the overparameterized model BO. However, we interpret a more parsimonious model El_Shade as better supported as it performed virtually as well (ΔAIC = 0.3; Burnham and Anderson, 2002) and note that five other models performed similarly (ΔAIC < 2).

We do not believe that our models described Minimum temperature behavior well (Table 1). The best-supported models for

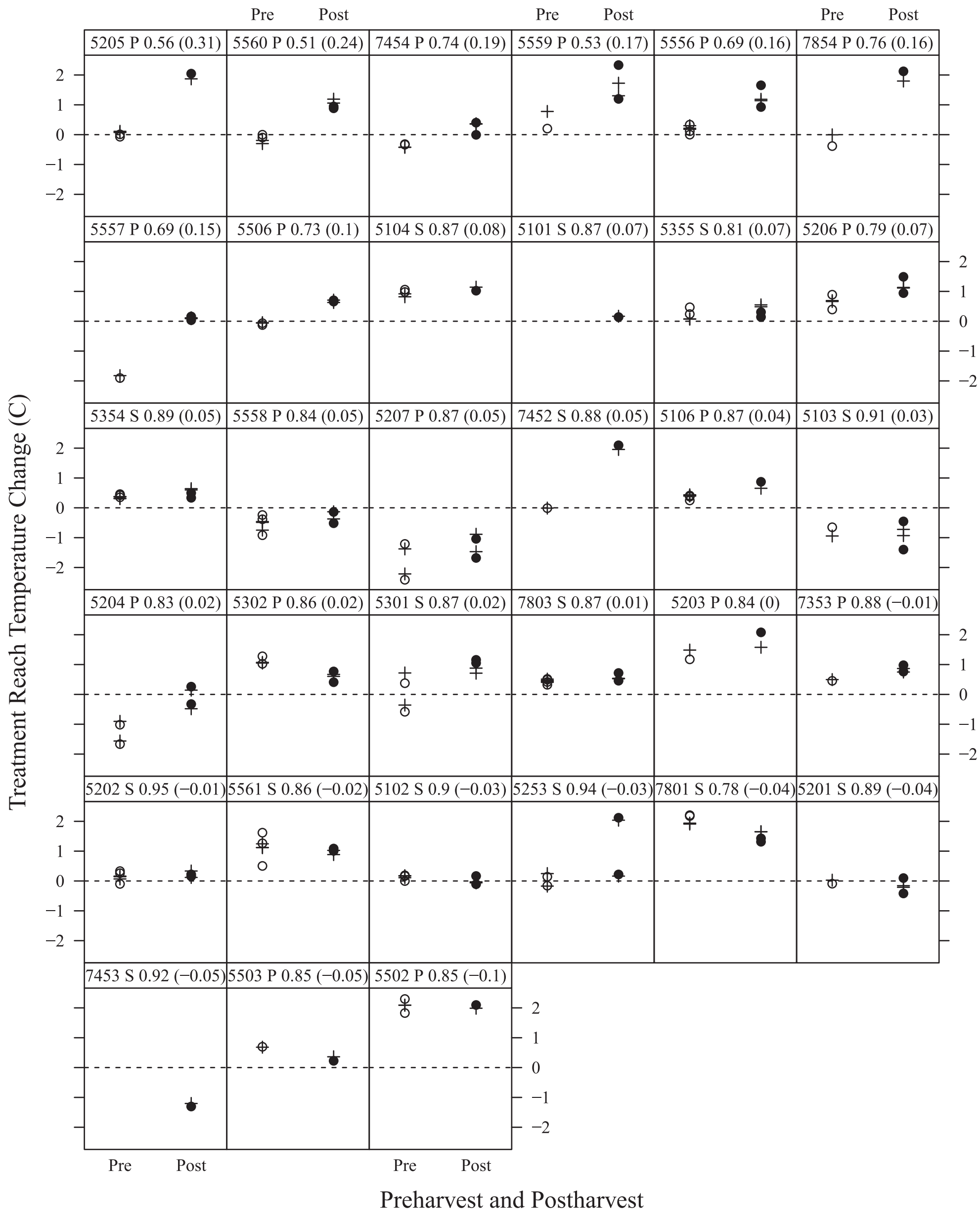


Fig. 3. Observed and predicted temperature changes for maximum temperatures (°C) by site. Pre-harvest and post-harvest observations are represented by open and filled circles, respectively. Each point represents one year of data collection at a site. The crosses represent predicted values from model Grad_Shade. Above each site's data is listed its site number, ownership ([S]tate or [P]rivate), post-harvest shade value, and in parentheses the change in shade value pre-harvest to post-harvest. Sites are ordered from the upper left to lower right by the observed change in shade values. Vertical differences of points within a pre-harvest or post-harvest category indicate a between-year change in the temperature relationship between Stations 1 and 2.

Author's personal copy

Table 5
Mean and range values for State and Private independent variables and site characteristics. Values are calculated from 15 State sites and 18 Private sites. Pre and Post refer to measurements taken preharvest or postharvest. For Shade ranges see Fig. 4; basal area and trees per hectare are BAPH and TPH, respectively.

Variable	State		Private	
	Mean	Range	Mean	Range
Gradient (%)	6.5	1.5–13.2	6.4	1.0–17.5
treatment Length (km)	0.8	0.3–1.5	0.6	0.3–1.8
Elevation (m)	350	160–570	300	3–900
Watershed area (ha)	222	72–593	208	27–626
Crown ratio	0.43	0.30–0.56	0.40	0.26–0.57
Buffer width (m)[a]	51.8	25–61	31	19–41
Bankfull width (m)	4.6	2.7–7.9	4.1	2.2–7
Wetted width (m)	2.3	1.3–3.7	2.0	1.0–3.0
Thalweg (cm)	17	9–30	15	8–24
Basal area (m /ha)				
Pre-harvest	41	19–74	43	23–73
Post-harvest	42	25–73	25	11–40
Trees per ha				
TPH pre	368	147–665	465	196–664
TPH post	387	128–645	270	111–429
Tree height (m)	26	17–37	25	18–31

[a] Means reported in Groom et al. (2011); 95% CI for State sites = 45.6 m, 58.0 m; 95% CI for Private sites = 26.7 m, 35.3 m.

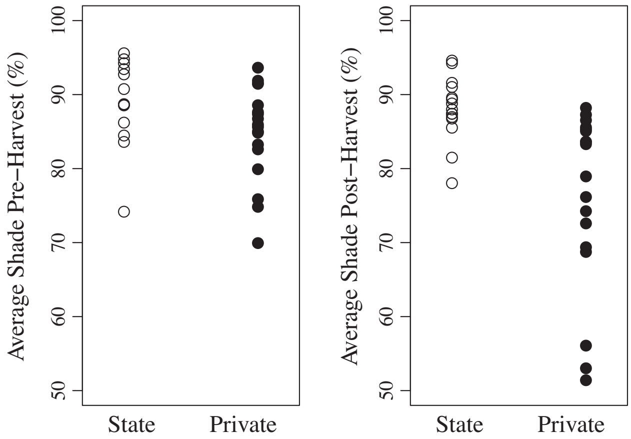


Fig. 4. Plot of average treatment reach shade values (%) for each site, grouped by harvest status (pre-harvest, post-harvest). On the left are state forest shade values, on the right shade are private forest values.

Minimum temperatures were StreamShade, Grad_Shade, and a model with an indicator variable for private sites post-harvest (Harvest_Private, combined weight = 0.59), with StreamShade receiving the most support. Shade appeared to be important; those models that contained SH provided a combined model weight of 0.74. However, the indicator variable that distinguished private sites post-harvest from all other observations (PP) explained the variation nearly as well as models that included SH (model weight for Harvest_Private = 0.15) while the remaining predictor variables improved model fit marginally.

Parameter estimates for the best-supported models retained directionality but contributed to model fit differently across temperature metrics (Table 4). For Maximum and Mean temperatures, the variable CT appeared to account for expected changes in the treatment reach given an observed temperature increase or decrease in the control reach. The decrease in temperature between Stations 1 and 2 on average resulted in an increase in temperature between Stations 2 and 3 and vice versa (Fig. 2). CT was not a significant parameter for Minimum temperatures or Diel Fluctuation. The parameters GR and EL were not strongly supported (Table 1) and exhibited overlap in their estimates at the extremes of observed values (Fig. 2). The directionality of parameter TR indicated that streams warmed with increasing treatment reach length. We estimated an increase in Maximum and Minimum temperatures of 0.73 and 0.59 °C per km, respectively (Fig. 2). Low SH values were associated with temperature increases in all models (Table 4).

Among explanatory variables, shade exhibited the greatest potential to alter stream temperatures with minimum shade levels producing a predicted increase of ~2 °C and maximum shade levels a temperature decrease of ~−1 °C (Fig. 2). We generally observed an increase in Maximum temperatures pre-harvest to post-harvest for sites that exhibited an absolute change in shade of >6%; otherwise, directionality appears to fluctuate (Fig. 3).

State and private sites exhibited similarities in the mean and range of their site values for gradient, treatment reach length, watershed area, crown ratio, wetted width, and pre-harvest vegetation metrics (Table 5). Following harvest, Maximum temperatures at private sites increased relative to state sites on average by 0.71 °C (Table 6, coefficient of PP, 95% CI = 0.51, 0.92). Similarly, Mean temperatures increased by 0.37 °C (0.24, 0.50), Minimum temperatures by 0.13 °C (0.03, 0.23), and Diel Fluctuation increased by 0.58 °C (0.41, 0.75). This increase appears to coincide with a decline in shade for some private sites (Fig. 4). Harvest on state sites did not produce a temperature change signal that differed from pre-harvest background levels. Models for Maximum, Mean, and Diel Fluctuation that considered state harvest to have negligible impact on stream temperature (Harvest_Private) received more support than those that considered it an influence (model Harvest_S_P; Table 1) with an observed ΔAIC increase respectively of 25.8, 16.2, and 5.9. The model which considered the variables PP and TL and their interaction (Harvest_PXLength) generally had greater explanatory power (lower ΔAIC) than the Harvest_Private models. However, the Harvest_PXLength model exhibited unexpected parameter estimates, indicating greater increases in private stream temperatures along shorter treatment reaches. A plot of post-harvest shade values against treatment reach length (Fig. 5A) suggests this relationship may be due to

Table 6
Fixed- and random-effect parameter values for the HarvestPrivate model fit by restricted maximum likelihood. Observations = 119, Groups (Sites) = 33. TRLength is expressed as change in temperature over 1 km.

Parameters	Maximum temperature				Mean temperature				Minimum temperature				Diel fluctuation			
Fixed	DF	Value	SE	p	DF	Value	SE	p	DF	Value	SE	p	DF	Value	SE	p
Intercept	33.9	0.280	0.143	0.058	32.7	0.191	0.088	0.037	32.3	0.152	0.060	0.017	33.1	0.076	0.116	0.515
CT	21.5	−0.798	0.520	0.140	18.8	−1.018	0.393	0.018	24.2	−0.407	0.315	0.209	23.4	-0.528	0.631	0.412
TL	30.2	0.745	0.335	0.034	29.4	0.602	0.208	0.007	27.8	0.538	0.141	0.001	30.1	0.216	0.275	0.440
PP	92	0.711	0.101	0.000	92.4	0.369	0.063	0.000	91	0.128	0.049	0.011	88.6	0.578	0.084	0.000
Random			Std.Dev				Std.Dev				Std.Dev				Std.Dev	
Intercept			0.535				0.206				0.091				0.355	
CT			4.554				1.596				1.036				7.008	
Residual			0.111				0.049				0.032				0.076	

Author's personal copy

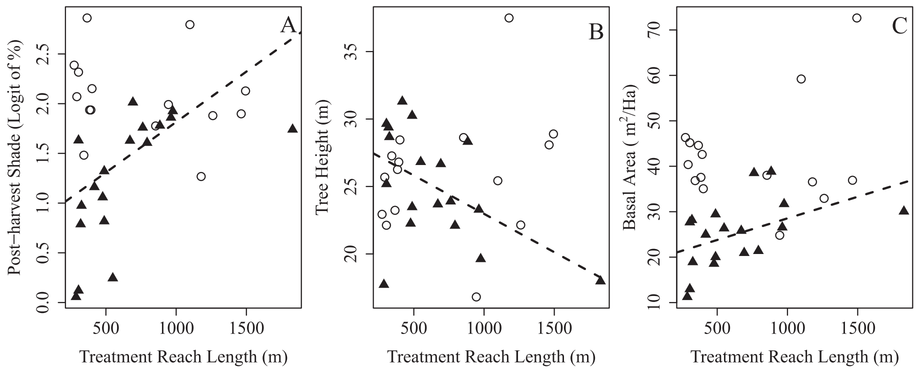


Fig. 5. Post-harvest values for treatment reach (A) logit-transformed percentages of mean shade values, (B) tree heights, and (C) basal area (m^2/Ha) by Treatment Reach length. Triangles represent privately-owned sites; circles are state sites. The dashed line represents the best linear fit for the filled circles (*y*-axis variable = intercept + *x*-axis variable). Shade values ranged from 0.51 to 0.95.

shade loss along the shorter private reaches. This in turn may be related to the presence of taller trees in the shorter reaches (Fig. 5B) or lower post-harvest basal area along the shorter reaches (Fig. 5C).

A comparison of within-site changes in Maximum temperatures pre-harvest to post-harvest indicated an overall increase in private site temperatures while observed changes at state sites were as frequently positive as negative (Fig. 6). The average of Maximum state site changes = 0.0 °C (range = −0.89 to 2.27 °C). Observed Maximum temperature changes at private sites averaged 0.73 °C (range = −0.87 to 2.50 °C), and exhibit a greater frequency of post-harvest increases from 0.5 to 2.5 °C compared to state sites. We repeated this comparison while controlling for the effects of control reach temperature change, treatment reach length, and gradient by plotting differences in partial residuals from the Maximum temperature model Grad_Shade (each datum = model residuals + predicted effect of Shade). We found that state site differences became less extreme for positive increases (<1.5 °C) while private comparisons appeared to occupy the same range of responses (Fig. 6).

3.2. Analysis II: shade

Correlations among shade variables were greatest for comparisons with BAPH. Sites with higher stocking levels, wider uncut buffers, or fewer stream banks harvested had greater basal area. The variable BAPH exhibited a positive Pearson's correlation with TPH (0.54) and Width (0.47) and a negative correlation with Nsides (−0.55). Variable combinations Height and CR were negatively correlated (−0.30) as were TPH and NSides (−0.52).

The shade model BasalXHeight which included parameters for basal area per hectare (BAPH), tree height, and their interaction was best-supported (Table 3; $\Delta AIC_c = 0.0$, $n = 33$, $R^2 = 0.69$, $\beta_{\text{intercept}} = 1.795$, $\beta_{\text{BAPH}} = 3.100e^{-2}$, $\beta_{\text{Height}} = -6.250e^{-2}$, $\beta_{\text{BAPA *Height}} = -4.680e^{-4}$, model $p < 0.001$) with an AIC_c distance of 10.7 between itself and the next-best supported model, BasalHeight (additive parameters BAPH and tree height). Its model weight ($\omega = 1.00$) indicated strong relative support for this model and virtually no support for the remaining models. The model BasalXHeight predicted
greater shade coverage with shorter trees and more basal area per hectare. An interpretation of the interaction term suggests that the effect of tree height is most acute for riparian areas with greater basal area. Residual, normal *q*–*q*, and standardized residual plots of the model parameterized by BAPH (BasalArea) indicated that certain points exhibited substantial leverage to the extent that a linear model may not be appropriate. Examination of paired variable plots suggested that plot blowdown may have influenced the leveraging outliers. A post hoc linear model that included plot blowdown in additional to basal area per hectare, tree height, and their interaction resolved the model fit issues and fit the data better than BasalXHeight (AIC_c = 7.5 lower than for BasalArea, $R^2 = 0.75$). However, site 5354 appeared responsible for contributing the blowdown effect; with its removal the interaction term in BasalXHeight ceased to confer statistical significance ($p = 0.18$) and BasalHeight graphically fits the data adequately ($R^2 = 0.70$). We did not find a relationship between hardwood predominance among sites and tree height; the Pearson's correlation between average percent hardwood at a site within 30 m of the stream and Height was 0.083 ($t = 0.466$, df = 31,

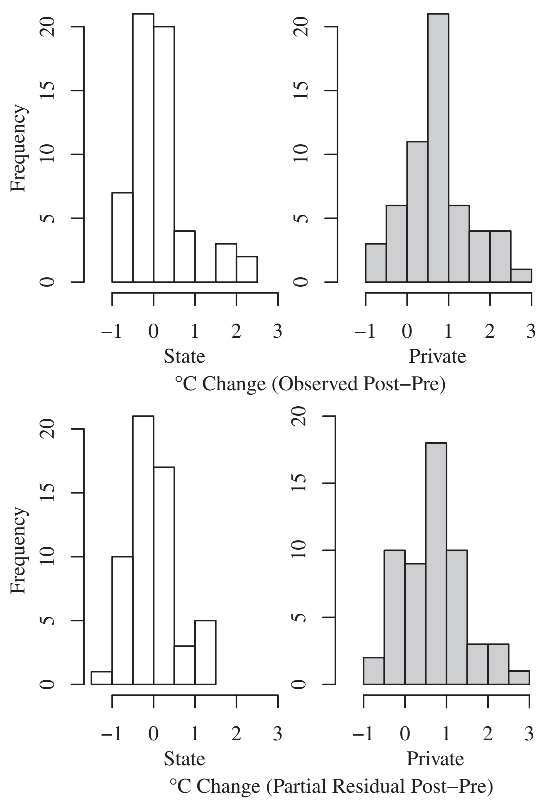


Fig. 6. Within-site pairwise differences in temperature change between post-harvest and pre-harvest values for Maximum observed data and partial residuals. Observed values are presented individually in Fig. 3. Partial-residual values represent observed values but control for site treatment reach length, upstream control temperature change, and stream gradient.

Author's personal copy

$p = 0.644$). An alternate shade model, BufferWidth (variables: number of sides harvested, buffer width, and their interaction; Table 3), contained no vegetation plot variable information, only the buffer width and number of riparian sides harvested. Its $\Delta \mathrm{AIC_c}$ value distanced it from the best-supported model yet it accounted for almost 50% of data variation ($n = 33$, $R^2 = 0.477$, $\beta_{\mathrm{intercept}} = 2.294$, $\beta_{\mathrm{NSides}} = -0.699$, $\beta_{\mathrm{BuffWidth}} = -4.470e^{-3}$, $\beta_{\mathrm{NSides*BuffWidth}} = 1.230e^{-2}$, model $p < 0.001$).

Private site shade values appeared to decrease pre-harvest to post-harvest. Private post-harvest shade values differed from pre-harvest values (mean change in Shade from 85% to 78%, $n_{\mathrm{Private}} = 18$, df = 17, paired $t = -3.678$, $p = 0.002$); however, no difference was found for state site shade values pre-harvest to post-harvest (mean change in Shade from 90% to 89%, $n_{\mathrm{State}} = 15$ df = 14, paired $t = -1.150$, $p = 0.269$). We did not find evidence that shade differed if one or both banks were harvested for private sites ($n_{\mathrm{SingleSide}} = 4$, $n_{\mathrm{TwoSides}} = 14$, df = 7.589, $t = 1.978$, $p = 0.085$) although the sample size for single sided harvests was low. Similarly, private site shade values did not appear to differ between Medium or Small streams ($n_{\mathrm{Small}} = 4$, $n_{\mathrm{Medium}} = 14$, df = 3.595, $t = -1.345$, $p = 0.257$).

4. Discussion

We estimated the magnitude of temperature changes by examining differences between pre- and post-harvest summer maximum temperatures, evaluating predicted variable contributions to temperature change, and comparing estimates of temperature change associated with private and state forests. Maximum, Average, Minimum, and Diel Fluctuation stream temperatures increased as a consequence of timber harvest on private forests. State forest stream temperature patterns remained similar before and after harvest. The increases on private sites coincide with a decline in shade due to timber harvest. In turn, the best predictor of post-harvest shade was a model including basal area within 30 m of a stream, tree height, and their interaction.

4.1. Shade and temperature change

A primary driver of changes in stream temperature was stream shade. For the four temperature values we examined, the mixed-effects models that included shade outperformed models that lacked shade. The best-supported shade models indicated that the lowest-observed shade value of 50% is associated with a predicted increase in Maximum stream temperatures by as much as 2 °C and for Minimum temperatures as little as 0.3 °C. At the greatest observed shade levels (96%) the predicted response for Maximum and minimum temperatures was −0.7 °C and −0.1 °C, respectively. This range of estimated temperature responses to site shade values is similar to results from a manipulative experiment by Johnson (2004). She determined that for a 200 m bedrock reach the temperature difference between 100% (artificial) shading and full exposure stream temperatures differed by about 4 °C. Similar to our regression estimates of negative Maximum stream temperatures at high shade values (−0.66 °C at 96% shade), Johnson found a decline of about 1 °C in maximum stream temperatures with 100% shade.

Other shade model parameter estimates indicated that stream temperatures were expected to increase with greater treatment reach lengths and low gradients (Table 4). The finding for treatment reach length is consistent with Caissie (2006), who reported general stream temperature increases with distance downstream. Our negative estimate for the coefficient of gradient indicated that temperature increases over the length of our treatment reaches were less for steeper reaches, a result that is echoed in Danehy et al. (2005), and that Subehi et al. (2009) attribute to the reduced residence time of water within the stream. An alternative explanation is that more frequent hyporheic exchange in steeper streams with step-pool morphologies may moderate stream temperatures (Anderson et al. 2005). Our negative relationship between temperature change in the control reach vs. the treatment reach was graphically described by Dent et al. (2008). They found that an abrupt temperature increase in the control reach was generally accompanied by an opposite change in the pre-harvest treatment reach. We suspect that local hydrological conditions at one of the control probe stations, resulting in locally warmer or cooler water temperatures (Bilby, 1984), could produced this temperature pattern. The temperature of the downstream station would not reflect this condition and would therefore appear to reverse the increase or decrease in temperature observed in the control reach.

4.2. Magnitude of temperature changes

The average increase in Maximum temperatures on private sites following timber harvest was estimated to be 0.7 °C. However, sites did not all behave similarly; some decreased in temperature while others exhibited higher increases. Although Mean, Minimum, and Diel Fluctuation temperatures also increased overall post-harvest, they similarly exhibited variability in response.

Overall, we did not observe a temperature increase on state sites as a result of timber harvest. While some changes in stream temperature were observed, state forest treatment effects were not substantial enough to support modeling them as differing from pre-harvest conditions. We interpret these results and the general lack of observed changes in stream temperature for state forest to indicate that treatment buffer widths and conditions on state forest sites were generally sufficient to protect against timber harvest-related increases in stream temperature. Even so, two state sites registered temperature changes between a pre-harvest year and a post-harvest year of >2.3 °C; after controlling for site factors the increases were <2 °C.

Our stream temperature models were parameterized using channel and local riparian conditions. We did not examine variables outside of study reaches such as the influence of proportion of watershed harvested. Solar exposure of clear-cut soils may affect evapotranspiration and soil temperatures (Kim and Ek, 1995). St-Hilaire et al. (2000) improved empirical stream temperature model fits by including the effect of solar exposure on soil temperatures. Hewlett and Fortson (1982) found that despite the presence of a 10–15 m wide riparian buffer along their study site in Georgia, USA, their study stream temperatures increased by more than 11 °C, much more than the authors estimated would occur under conditions of complete riparian zone removal. The authors suspected, based on ancillary data, that effluent groundwater may have been warmed in the exposed areas and then flowed into their study stream. However, a follow-up study on the same site with a more substantial riparian buffer has found no temperature increase (Dr. Rhett Jackson, Univ. of Georgia, personal communication). Bourque and Pomeroy (2001) found a relationship between stream temperature gains and proportions of upstream catchments harvested. Pollock et al. (2009) similarly found a relationship between proportion of a watershed harvested and maximum stream temperatures, although Ice et al. (2010) argue that these results are best explained by riparian conditions such as shade and channel conditions. Our models appear to have explained a substantial portion of the observed variability in stream temperature and relationships to timber harvest; however, these factors may have played an additional role in influencing our sites' stream temperatures.

The magnitudes of change in observed stream temperatures reported for this study are similar to findings from other studies which evaluated contemporary harvest practices with riparian buffers and substantially lower than values associated with older har-

Author's personal copy

vest practices or harvesting without buffers. Levno and Rothacher (1967) found maximum temperature increases of 2.23 °C after harvest but before stream scouring (logging debris partially shaded the stream) and 6.67 °C increase post-scour. During the years 1965–1967 in the Alsea Watershed Study maximum water temperature increased 10 °C at the bottom of the Needle Branch Watershed following logging to the stream's edge, stream cleaning, and slash burning (Ice, 2008). Gomi et al. (2006) found that for four headwater streams subject to clearcut harvesting with no buffer retention, daily maximum temperatures increased between 1.9 and 8.8 °C while increases for streams with buffers ranged from 1.1 to 4.1 °C, similar to our findings.

Gomi et al. (2006) reported that treatment effects were more subdued post-harvest with inclusion of a 30 m buffer; maximum daily temperatures increased by <2 °C. When examining streams with 10 m buffers, Jackson et al. (2001) found that two out of three streams produced an increase of <2.4 °C and the third a change of −0.3 °C. Wilkerson et al. (2006) studied stream water temperature response to harvesting in Maine with different buffer widths. Streams without buffers experienced the largest temperature increases (1.4–4.4 °C). Stream with 11 m buffers showed small, but not statistically significant increases (1.0–1.4 °C) while streams with 23 m buffers as well as sites with partial harvest treatments showed no temperature increases. The results from these contemporary studies including our findings for our private forest sites indicate that some buffer retention practices likely reduce the magnitude of change but do not necessarily completely eliminate harvest effects on stream temperature. However, temperature increases and shade decreases were not ubiquitous among private sites; some did not indicate increases in temperature following harvest (Fig. 3). Other site conditions likely drove this observed range of response.

4.3. Relationships between shade and riparian characteristics

Increases in stream temperature were related to decreases in shade, both of which only occurred on private sites. These results coincide with the findings of Groom et al. (2011). However, there were ranges in shade and temperature responses on private sites reflecting variability in riparian conditions after harvesting according to minimum Forest Practices Act regulations. The variability may have been related to site differences in shade and factors related to shade.

Between 68% and 75% of variability in post-harvest shade may be accounted for by basal area within 30 m of the stream, tree height, and possibly blowdown. Sites with higher basal area within 30 m of the stream resulted in higher post-harvest shade. We anticipated that the variable TPH would inform regression models containing basal area per hectare (BAPH), as total basal area would depend on number of trees as well as tree size. The shade model ranking indicated that inclusion of the TPH variable or its interaction with BAPH did not improve model fit; given their correlation, we believe the two variables shared a similar relationship over this landscape.

Our findings suggest that sites with shorter trees had higher post-harvest shade. DeWalle (2010) found in a modeling study that buffer height and density were as important as buffer width at providing shade. However, their results predicted an increase of shade values with tree height which is counter to our findings. It may be possible that our negative relationship between tree height and shade is due to the negative correlation between crown ratios and tree height. Buffers comprised of trees with canopies tens of meters above the stream may not protect streams from mid-morning or afternoon sun exposure. We observed that private sites with low basal area generally had taller trees. The relationship between the percent stream basal area represented by hardwoods and height was not significant, suggesting that hardwood/conifer dominance did not play a role. The negative relationship between plot blowdown basal area values and stream shade appears reasonable, although the blowdown effect may be driven by extensive plot blowdown at a single site.

We found that modeling stream shade as a function of riparian buffer width and the number of stream banks harvested informative. While not as good a predictor as basal area, this model did explain 50% of the observed variability in post-harvest shade. Collectively the two models suggest that harvesting timber within riparian areas on both sides of the stream, reducing basal area and leaving narrower buffers are actions which contribute to decreases in shade.

5. Conclusion

Two years following timber harvest in our Oregon Coast Range streams, Maximum, Mean, Minimum, and Diel Fluctuation summer temperatures increased along some sites. We detected no differences between pre-harvest and post-harvest stream temperature on state forests, indicating that state forest riparian buffers prevent harvest-related increases in shade and stream temperature. Temperature increases on private sites were related to reduction in shade. Reductions in shade were related to decreases in basal area for sites with greater tree heights. Results correspond with the finding of elevated stream temperatures for private sites post-harvest in the Groom et al. (2011) temperature standard analysis. Although our study's inference is limited to the Oregon Coast Range, our determination of the relative efficacy of different buffer designs at influencing shade and stream temperatures are likely relevant to other high-rainfall low-order Douglas Fir dominated streams in the Pacific Northwest that are subject to similar harvest practices.

Role of the funding source

The Oregon Department of Forestry Private Forest Division and State Forest Division provided substantial project funding, conducted data collection, developed the study design, and assisted in the analysis, interpretation of data, writing of the report, and decision to submit the work for publication. This Project has been funded wholly or in part by the United States Environmental Protection Agency (EPA) under assistance agreement C9-00045105 to the Oregon Department of Environmental Quality. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. The EPA only provided financial support; ODEQ additionally provided a representative to serve on the project's External Review Committee.

Acknowledgements

We thank Kyle Abraham, Jerry Clinton, Kevin Nelson, Kristin Cotugno, Marganne Allen, Peter Daugherty, and Jeff Brandt for technical and administrative support. We thank members of the External Review Committee for their guidance and feedback and field interns for their data collection efforts. We also thank the private forest landowners and Oregon state forest managers who have committed to operating around and maintaining the integrity of these study sites for the duration of the study.

Author's personal copy

References

Allen, M., Dent, L., 2001. Shade conditions over forested streams in the Blue Mountain and Coast Range georegions of Oregon. Oregon Department of Forestry Technical Report #13, pp. 101.

Anderson, J.K., Wondzell, S.M., Gooseff, M.N., Haggerty, R., 2005. Patterns in stream longitudinal profiles and implications for hyporheic exchange flow at the H.J Andrews Experimental Forest, Oregon, USA. Hydrol. Processes 19, 2931–2949.

Bartholow, J.M., 1989. Stream temperature investigations: field and analytic methods. Instream flow information paper No. 13, US Fish and Wildlife Service Biological Report 89 (17), pp. 139.

Bilby, R.E., 1984. Characteristics and frequency of cool-water areas in a western Washington stream. J. Freshwater Ecol. 2, 593–602.

Bourque, C.P.-A., Pomery, J.H., 2001. Effects of forest harvesting on summer stream temperatures in New Brunswick, Canada: an inter-catchment, multiple-year comparison. Hydrol. Earth Sys. Sci. 5, 599–613.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference. A Practical Information-Theoretic Approach, second ed. Springer-Verlag, New York, pp. 488.

Brosofske, K.D., Chen, J., Naiman, R.J., Franklin, J.F., 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecol. Appl. 7, 1188–1200.

Brown, G.W., 1969. Predicting temperatures of small streams. Water Resour. Res. 5, 68–75.

Brown, G.W., Krygier, J.T., 1970. Effects of clear-cutting on stream temperature. Water Resour. Res. 6, 1133–1139.

Caissie, D., 2006. The thermal regime of rivers: a review. Freshwat. Biol. 51, 1389–1406.

Danehy, R.J., Colson, C.G., Parrett, K.B., Duke, S.D., 2005. Patterns and sources of thermal heterogeneity in small mountain streams within a forested setting. Forest Ecol. Manag. 208, 287–302.

Davies-Colley, R.J., Quinn, J.M., 1998. Stream lighting in five regions of North Island, New Zealand: control by channel size and riparian vegetation. N. Z. J. Mar. Freshwater Res. 32, 591–605.

Dent, L., Vick, D., Abraham, K., Shoenholtz, S., Johnson, S., 2008. Summer temperature patterns in headwater streams of the Oregon Coast Range. J. Am. Water Resour. Assoc. 44, 803–813.

DeWalle, D.R., 2010. Modeling stream shade: riparian buffer height and density as important as buffer width. J. Am. Water Resour. Assoc. 46, 323–333.

Feller, M.C., 1981. Effects of clearcutting and slash burning on stream temperature in southwestern British Columbia. Water Resour. Bull. 17, 863–867.

Gomi, T., Moore, R.D., Dhakal, A.S., 2006. Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia. Water Resour. Res. 42, W08437. doi:10.1029/2005WR004162.

Groom, J.D., Dent, L., Madsen, L.J., 2011. Stream temperature change detection for state and private forests in the Oregon Coast Range. Water Resour. Res. 47, W01501. doi:10.1029/2009WR009061.

Harris, D.D., 1977. Hydrologic changes after logging in two small Oregon coastal watersheds. US Geological Survey Water-Supply Paper 2037, Washington DC, 31 pp.

Hawkins, C.P., Hogue, J.N., Decker, L.M., Feminella, J.W., 1997. Channel morphology, water temperature, and assemblage structure of stream insects. J. N. Am. Benthol. Soc. 16, 728–749.

Hewlett, J.D., Fortson, J.C., 1982. Stream temperature under an inadequate buffer strip in the Southeast Piedmont. Water Resour. Bull. 18, 983–988.

Holtby, B., Newcombe, C.P., 1982. A preliminary analysis of logging-related temperature changes in Carnation Creek, British Columbia. In: Hartman, G.F. (Ed.), Proceedings of the Carnation Creek Workshop: A 10-year Review, Canada Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, British Columbia, Canada, pp 81–99.

Hurvich, C.M., Tsai, C.-L., 1989. Regression and time series model selection in small samples. Biometrika 76, 297–307.

Ice, G.G., 2008. Stream temperature and dissolved oxygen. In: Stednick, J.D. (Ed.), Hydrological and Biological Responses to Forest Practices: The Alsea Watershed Study. Springer, New York, pp. 37–54.

Ice, G.G., Brown, G.W., Gravelle, J.A., Jackson, C.R., Light, J.T., Link, T.E., Martin, D.J., McGreer, D.J., Skaugset, A.E., 2010. Discussion: stream temperature relationships to forest harvest in Western Washington. J. Am. Water Resour. Assoc. 48, 838–842.

Isaak, D.J., Hubert, W.A., 2001. A hypothesis about factors that affect maximum summer stream temperatures across montane landscapes. J. Am. Water Resour. Assoc. 37, 351–366.

Isaak, D.J., Luce, C.H., Rieman, B.E., Nagel, D.E., Peterson, E.E., Horan, D.L., Parkes, S., Chandler, G.L., 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecol. Appl. 20, 1350–1371.

Jackson, C.R., Sturm, C.A., Ward, J.M., 2001. Timber harvest impacts on small headwater stream channels in the coast ranges of Washington. J. Am. Water Resour. Assoc. 37, 1533–1549.

Johnson, S.L., 2004. Factors influencing stream temperature in small streams: substrate effects and a shading experiment. Can. J. Fish. Aquat. Sci. 57 (Suppl. 2), 30–39.

Johnson, S.L., Jones, J.J., 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Can. J. Fish. Aquat. Sci. 57, 30–39.

Kasahara, T., Wondzell, S.M., 2003. Geomorphic controls on hyporheic exchange flow in mountain streams. Water Resour. Res. 39, 1005. doi:10.1029/2002WR001386.

Kaufmann, P.R., Robison, E.G., 1998. Section 7: physical habitat characterization. In: Lazorchak, J.M., Klemm, D.J., Peck, D.V. (Eds.), Environmental Monitoring and Assessment Program-Surface Waters: Field Operations and Methods for Measuring the Ecological Condition of Wadeable Streams. EPA/620/R-94/004F.US Environmental Protection Agency. Washington, D.C.

Kim, J., Ek, M., 1995. A simulation of the surface energy budget and soil water content over the Hydrologic Atmospheric Pilot Experiments–Modélisation du Bilan Hydrique forest site. J. Geophys. Res. 100, 845–854.

Levno, A., Rothacher, J., 1967. Increases in Maximum Stream Temperatures After Logging in Old-growth Douglas-fir Watersheds. Research Note PNW-65. USDA Forest Service, Portland, OR.

Lewis, T. E., Lamphear, D.W., McCanne, D.R., Webb, A.S., Krieter, J.P., Conroy, W.D., 1999. Executive summary: Regional assessment of stream temperatures across northern California and their relationship to various landscape-level and site-specific attributes, Forest Science Project, Humboldt State University Foundation, Arcata, California, 14 pp.

Moore, R.D., Spittlehouse, D.L., Story, A., 2005. Riparian microclimate and stream temperature response to forest harvest: a review. J. Am. Water Resour. Assoc. 41, 813–834.

Moore, R.D., Wondzell, S.M., 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. J. Am. Water Resour. Assoc. 41, 763–784.

Neter, J., Kutner, M.H., Nachtsheim, C.J., Wasserman, W., 1996. Applied Linear Statistical Models, fourth ed. McGraw Hill.

Oregon Department of Forestry, 2001. Northwest Oregon state forests management plan appendix J: management standards for aquatic and riparian areas. Oregon Department of Forestry, Salem, Oregon.

Oregon Department of Forestry, 2007. Oregon Forest Practices Act Water Protection Rules: Riparian Management areas and Protection Measures for Significant Wetlands. Oregon Administrative Records Chapter 629, Division 635 and 645, Oregon Department of Forestry, Salem, Oregon.

Oregon Watershed Enhancement Board, 1999. The Oregon Plan for Salmon and Watersheds Water Quality Monitoring Technical Guide Book. Oregon Watershed Enhancement Board, Salem, Oregon. 159 pp. http://www.oregon.gov/OWEB/docs/pubs/wq_mon_guide.pdf (accessed 08.04.2011).

Pinheiro, J.C., Bates, D.M., 2000. Mixed-effects Models in S and S-Plus. Springer-Verlag, New York, 528 pp.

Pollock, M.M., Beechie, T.J., Liermann, M., Bigley, R.E., 2009. Stream temperature relationships to forest harvest in western Washington. J. Am. Water Resour. Assoc. 45, 141–156.

Poole, G.C., Berman, C.H., 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environ. Manag. 27, 787–802.

Quinn, J.M., Wright-Stow, A.E., 2008. Stream size influences stream temperature impacts and recovery rates after clearfell logging. Forest Ecol. Manag. 256, 2101–2109.

Richter, A., Kolmes, S.A., 2005. Maximum temperature limits for chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest. Rev. Fish Sci. 13, 23–49.

Sinokrot, B.A., Stefan, H.G., 1993. Stream temperature dynamics: measurements and modeling. Water Res. 29, 2299–2312.

Sridhar, V., Sansone, A.L., LaMarche, J., Dubin, T., Lettenmaier, D.P., 2004. Prediction of stream temperature in forested watersheds. J. Am. Water Resour. Assoc. 40, 197–213.

Subehi, L., Fukushima, T., Onda, Y., Mizugaki, S., Gomi, T., Terajima, T., Kosugi, K., Hiramatsu, S., Kitahara, H., Kuraji, K., Ozaki, N., 2009. Influences of forested watershed conditions on fluctuations in stream water temperature with special reference to watershed area and forest type. Limnology 10, 33–45.

St-Hilaire, A., Morin, G., El-Jabi, N., Caissie, D., 2000. Stream temperature modelling in a small forested stream: implications of forest canopy and soil temperature. Can. J. Civ. Eng. 27, 1095–1108.

Torgerson, C.E., Price, D.M., Li, H.W., McIntosh, B.A., 1999. Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. Ecol. Appl. 9, 301–319.

Valverde, T., Silvertown, J., 1997. Canopy closure rate and forest structure. Ecology 78, 1555–1562.

Wilkerson, E., Hagan, J.M., Siegel, D., Whitman, A.A., 2006. The effectiveness of different buffer widths for protecting headwater stream temperature in Maine. For. Sci. 52, 221–231.

Zuur, A.F., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R. Springer.