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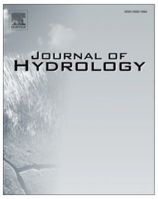

Catchment-scale stream temperature response to land disturbance by wildfire governed by surface–subsurface energy exchange and atmospheric controls

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SUMMARY

In 2003, the Lost Creek wildfire severely burned 21,000 hectares of forest on the eastern slopes of the Canadian Rocky Mountains. Seven headwater catchments with varying levels of disturbance (burned, post-fire salvage logged, and unburned) were instrumented as part of the Southern Rockies Watershed Project to measure streamflow, stream temperature, and meteorological conditions. From 2004 to 2010 mean annual stream temperature (T_s) was elevated 0.8–2.1 °C in the burned and post-fire salvage logged streams compared to the unburned streams. Mean daily maximum T_s was 1.0–3.0 °C warmer and mean daily minimum T_s was 0.9–2.8 °C warmer in the burned and post-fire salvage logged streams compared to the unburned catchments. The effects of wildfire on the thermal regime of the burned catchments were persistent and trend analysis showed no apparent recovery during the study period. Temporal patterns of T_s were strongly associated with seasonal variability of surface and groundwater interactions and air temperature. Advective heat fluxes between groundwater and surface water were likely the dominant controls on T_s, though the strength of these advective controls varied among catchments highlighting the importance of simultaneous catchment-scale and process-focused research to better elucidate the physical drivers influencing T_s response to disturbance.

1. Introduction

There is a significant body of literature demonstrating the impacts of land use activities, including forestry, agriculture, industrialization, urbanization, and river impoundment on stream temperature (Webb et al., 2008). More recently, there has been increasing concern regarding the effects of climate change and related natural disturbances (e.g., wildfire, pest outbreaks) on the short and long term temperature dynamics in streams (Eaton and Scheller, 1996; Mahlum et al., 2011; Schindler, 2001). In the last several decades, wildfire frequency, intensity, severity, and area burned have increased in many regions throughout the world (Pechony and Shindell, 2010; Westerling et al., 2006; 2011). These trends in climate change associated shifts in wildfire regimes underscores the need to address knowledge gaps on the magnitude and extent of the initial effects of fires on stream temperature, the rates of recovery to pre-fire conditions or to a new stable state, and the underlying mechanisms that drive stream temperature responses to disturbance in different environments.

Following wildfire, salvage harvesting operations often occur in an attempt to recover damaged timber, recoup economic losses, improve human safety, and to mitigate the potential for pest outbreaks (e.g., spruce bark beetle) (Lindenmayer et al., 2004). In some environments, these activities have the potential to produce greater ecosystem impacts than the disturbance alone, including increased erosion and runoff, loss of essential terrestrial and aquatic

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habitat, and delayed or impaired ecosystem recovery (Karr et al., 2004). However, the magnitude and duration of the impacts on water quality – specifically stream temperature – from salvage harvesting remain poorly understood.

Stream temperature is fundamental to water quality and is responsible for driving a variety of biotic and abiotic processes in lotic systems. Stream temperature can influence the dissolved oxygen concentration, nutrient uptake/release rates from sediments, and the physiology (activity, metabolism, growth, and reproduction) of plants and animals (Butcher and Covington, 1995; Cerco, 1989). Temperature is the most critical habitat determinant for many aquatic organisms, including fish, insects, zooplankton, and phytoplankton, with most species limiting their thermal exposure to a narrow temperature range (Beitinger and Fitzpatrick, 1979; Vannote and Sweeney, 1980). For example, maximum temperature and diel heating and cooling of the stream environment strongly affect the distribution of some cold-adapted taxa, including *Salvelinus confluentus* (bull trout) and "threatened" species *Oncorhynchus clarkii lewisi* (westslope cutthroat trout) (Bear et al., 2007; Dunham et al., 2003; Selong et al., 2001). Moreover, increases in stream temperature have been suggested to increase hybridization between introduced *O. mykiss* (rainbow trout) and native westslope cutthroat trout, further reducing spatial distribution of threatened pure-strain westslope cutthroat trout (Rasmussen et al., 2010; Wenger et al., 2011). Thus, long-term increases or rapid fluctuations in stream temperature following land use activities or natural disturbances may have adverse effects on life history patterns of aquatic biota, lead to stress for many species, and influence the spatial heterogeneity of stream ecosystems (Isaak et al., 2012; Johnson and Jones, 2000).

Stream temperature is governed by discrete fluxes of heat energy that fluctuate spatially and temporally in a catchment. Lotic heat budget studies demonstrate that patterns of stream temperature are affected by non-advective energy exchange through net radiation, friction of the water with the stream bed and banks, as well as latent and sensible heat transfer from the atmosphere (Leach and Moore, 2010; Sinokrot and Stefan, 1993; Webb and Zhang, 1997). In some environments, advective energy exchanges (e.g., direct precipitation inputs, tributary inflows, subsurface hillslope runoff, conduction from the stream bed, hyporheic flows, and aquifer discharge/recharge) are important sources of heat energy exchange (Arrigoni et al., 2008; Constantz, 1998; Tague et al., 2007). In particular, groundwater temperatures can be relatively constant – as groundwater contributions increase, surface temperature variations are typically moderated from atmospheric influences (Anderson, 2005). The interaction among various heat fluxes can create heterogeneity in spatial (longitudinal, lateral, and vertical) and temporal temperature patterns, which can confound the interpretation of stream temperature data (Ebersole et al., 2003; Hannah et al., 2008; Leach and Moore, 2011).

This study examined the effect of land disturbance by wildfire on stream temperature dynamics in burned, post-fire salvage logged, and unburned (reference) catchments for a period of seven years in the eastern slopes of the Rocky Mountains in Alberta, Canada. The magnitude of impact from wildfire on stream temperature in this environmental setting is uncertain because groundwater discharge is a large component of the annual hydrograph in this region. Moreover, the duration of impacts on post-fire stream temperatures is largely unknown as the majority of studies are short duration (<5 years). The objectives of this study were to (1) measure and compare diel, monthly, and annual stream temperature regimes in unburned and disturbed (burned and post-fire salvage logged) headwater catchments, (2) to document the longer-term (7 years) trajectory of impacts of wildfire on stream temperature, and (3) to evaluate the potential drivers (dominant physical controls) of stream temperature across catchments.

2. Methods

2.1. Study area

From July 23 to August 25, 2003 the Lost Creek wildfire burned more than 21,000 hectares (51,800 acres) of forested land in the Crowsnest Pass of south-west Alberta, Canada (49° 34′ N, 114° 31′ W) and was one of the most severe fires in the Rocky Mountain east slope forests since the 1930s. The fire burned almost entirely as a continuous crown fire aided by high winds. While the proportion of area burned in individual catchments may be less than 100% (Table 1), almost all of the forest canopy, understory, and forest floor organic material in the burned catchments were consumed by wildfire. The "unburned" area in the disturbed watersheds is primarily composed of high elevation alpine areas lacking any significant tree cover. In March 2004, the Southern Rockies Watershed Project (SRWP) was initiated to investigate the ecohydrologic impacts of this major wildfire on headwater streams and to document the anticipated changes to regional water quality. The initial study design consisted of three burned catchments (South York Creek, Lynx Creek, and Drum Creek) and two unburned catchments (Star Creek and North York Creek) serving as references for comparison. These study catchments, except Drum, form the northern tip of the Flathead mountain range at the northern end of the fire boundary, an area which had no significant logging disturbance prior to the wildfire. In 2005, two additional post-fire salvage logged catchments in the Blairmore mountain range were instrumented (Lyons West Creek and Lyons East Creek). In total, seven catchments were fully instrumented to continuously record meteorological and hydrological data throughout the study period (Fig. 1).

All seven study catchments have north to north-easterly aspects with moderate sloping topography. Surficial geology is dominated by the Alberta Group and Blairmore Group, with lesser areas of the Belly River Group (Prior et al., 2013). In the study region, these geologic groups are characterized primarily by shale, sandstone, mudstone, and limestone. Soils are predominantly poorly developed Brunisols (Cambisols [FAO], Inceptisols [U.S. Soil Taxonomy]), which are imperfectly to well drained and typical of high elevation, forested landscapes. Streams within the study catchments are nival, freestone systems with oligotrophic nutrient regimes. Hydro-climatic variability reflects the upper end of streamflow and precipitation observed for the province of Alberta. The long term mean annual streamflow was 677 mm year^{-1}, ranging from 382 to 1102 mm year^{-1}. The mean annual precipitation was 801 mm year^{-1}, ranging from 381 to 1358 mm year^{-1} (Table 2). At lower elevations, the study catchments are dominated by stands of lodgepole pine (*Pinus contorta* var. *latifolia*), trembling aspen (*Populus tremuloides*) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) with vegetation at higher elevations comprising Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) and alpine meadows. For additional descriptions of the SRWP study area, see Bladon et al. (2008) or Silins et al. (2009a).

2.2. Data

2.2.1. Stream temperature (T_s)

Mean daily stream temperatures (T_s) were determined from hourly measurements collected with HOBO Temperature Data Loggers placed in a submersible plastic case or HOBO Temperature and Water Level Loggers (Model # H08-001-02 and U20-001-04; Onset Computer Corporation, Pocasset, MA, USA) deployed at each hydrometric station. Sensors were sheltered from direct radiation by placing rocks over top of the submersible plastic cases containing the H08 sensors or by placing the U20 sensors within a stilling

Table 1
Description of study catchments.Description of study catchments.

Catchment	Total area (ha)	Mean elevation (Range; m)	Mean catchment/stream slope (degrees)	Burned area (ha)	Burned area (%)	Salvage logged area (ha)	Salvage logged area (%)
Unburned (Reference)							
Star	1035	1853 (1482–2632)	24/6	0	0	–	–
North York	865	1917 (1552–2657)	25/8	1	0	–	–
Burned							
South York	365	1965 (1682–2639)	22/7	196	54	–	–
Lynx	781	1915 (1634–2641)	23/8	512	65	–	–
Drum	719	1727 (1430–2162)	26/8	718	100	–	–
Burned and salvage logged							
Lyons East	1309	1682 (1441–2029)	18/6	1067	81	238	18
Lyons West	684	1667 (1457–2073)	15/5	406	59	260	38

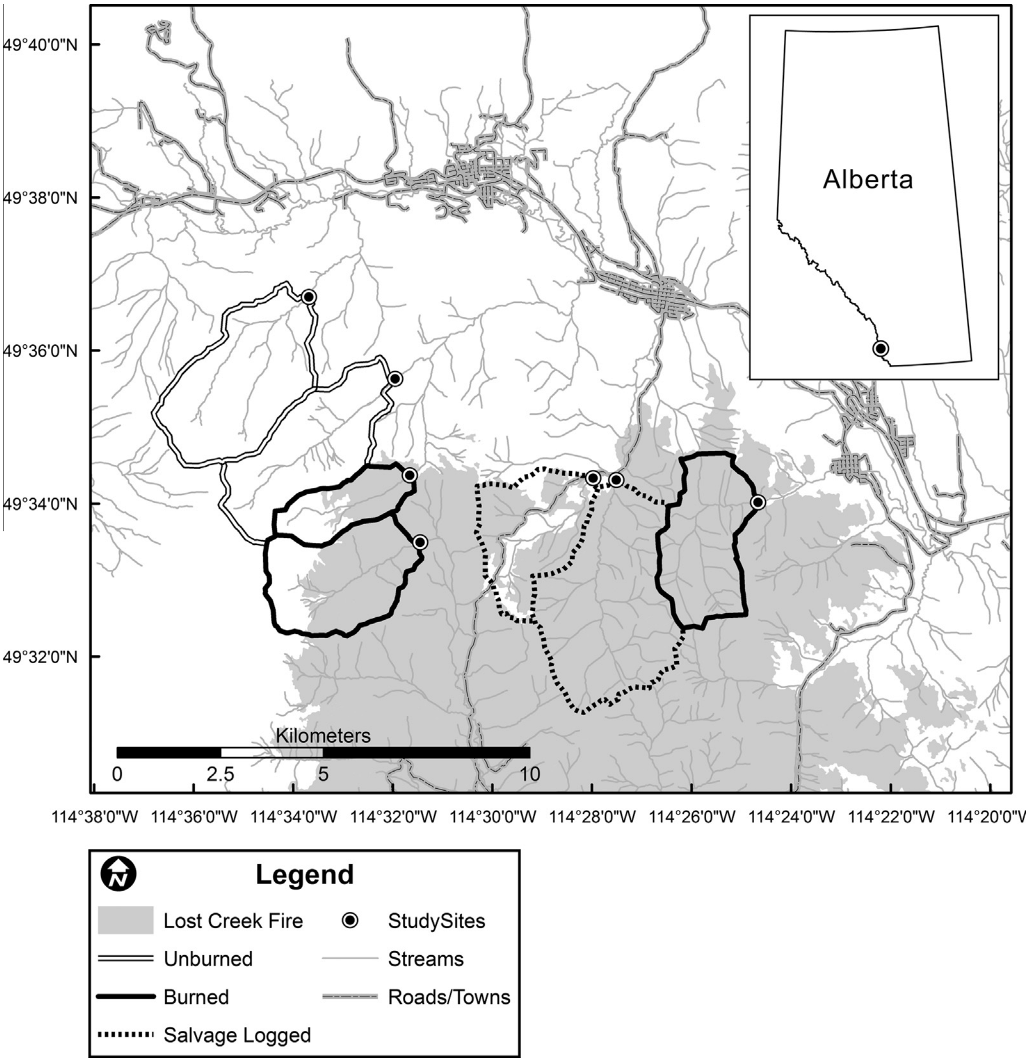

Fig. 1. Map of study catchments showing study area and northern extent of the 2003 Lost Creek wildfire. Catchments from West to East: Star Creek, North York Creek, South York Creek, Lynx Creek, Lyons West Creek, Lyons East Creek, and Drum Creek.

well, constructed from 4 inch ABS pipe. Additional T_s data measured at each hydrometric site were used to fill in missing values where primary temperature sensors were frozen, lost, or removed for maintenance. These data were obtained from adjacent HOBO U20 Water Level Data Loggers or from YSI Multi Parameter Water Quality Monitoring Sondes equipped with 6560 conductivity/temperature probes (Sonde Models 6820 and 6920; YSI Inc., Yellow Springs, OH, USA). Data from temperature sensors used to fill data gaps were recorded at a higher accuracy and resolution than those used the majority of the study period. Details and specifications of each sensor are listed in Table 3.

2.2.2. Air temperature (T_a)

Mean daily air temperature (T_a) in burned and unburned catchments was calculated from 10 min continuous records using a Campbell Scientific CR10X datalogger (Logan, UT, USA) measured

Table 2
Mean annual precipitation and streamflow by treatment (mm year^{-1}).

	2004	2005	2006	2007	2008	2009	2010	Grand mean
Precipitation (mm year^{-1})								
Unburned	612	1091	869	738	688	761	795	793
Burned	680	1358	1046	900	890	922	966	966
Salvage logged	–	381	746	582	616	695	694	619
Streamflow (mm year^{-1})								
Unburned	663	1062	578	581	544	474	662	652
Burned	871	1102	626	705	576	726	898	786
Salvage logged	–	699	602	382	458	393	506	507

Table 3
Instrumentation description and specifications. Deployment refers to the specific location that instrumentation was deployed within burned (BB), unburned (UB) and post-fire salvage logged catchments (SL).

Parameter	Instrument	Accuracy	Resolution	Deployment
Stream temperature	H08-001-02	±0.70 °C @ 21 °C	±0.4 °C @ 21 °C	BB, UB
	U20-001-04	±0.37 °C @ 20 °C	±0.1 °C @ 20 °C	BB, UB, SL
	YSI 6560 Probe	±0.15 °C @ 25 °C	±0.01 °C @ 20 °C	BB, UB, SL
Air temperature	HMP 50	±0.40 °C @ 20 °C	±0.1 °C @ 20 °C	BB, UB
	HMP 35C	±0.40 °C @ 20 °C	±0.1 °C @ 20 °C	BB, UB
Stream level	U20-001-04	±0.3 cm	±0.14 cm	BB, UB, SL
	Waterlog H350L/H355	±0.4 cm	0.000004 cm	BB, UB
Stream discharge	Swoffer 2100	±1.0%	0.001 m s^{-1}	BB, UB, SL
	Flow tracker ADV	±1.0%	0.0001 m s^{-2}	BB, UB, SL

with a Vaisala HMP50 or HMP35C Relative Humidity and Temperature Probe (Vaisala Oyj, Helsinki, Finland) mounted 3 m above the ground surface, within 10 m of the T_s sensors. T_a sensors were not installed until late 2004, thus only T_a data from 2005 to 2010 was used in the analysis. No T_a sensors were deployed in the salvage logged catchments (Lyons East and West Creeks). However, given the close proximity and elevation to Drum Creek (burned catchment), T_a data from the Drum Creek climate station was considered to be representative of T_a in salvage logged catchment. Riparian conditions in burned catchments were similar to those of the salvage logged catchments due to riparian buffers of burned trees remaining in place following salvage logging operations in the Lyons Creek catchments.

2.2.3. Stream discharge (Q)

Instantaneous stream discharge (Q) was determined using standard velocity area techniques with either a Swoffer current meter (Model 2100, Swoffer Instruments Incorporated, Seattle, WA, USA) or a Sontek acoustic doppler velocity meter (Flow Tracker ADV, Sontek/YSI, San Diego, CA, USA). The accuracy and resolution of these two current meters are listed in Table 3. Discharge was measured approximately every 7 days throughout the snow free period and on a monthly basis during winter at the same locations as stream temperature sensors. Stage-discharge relationships were derived for each stream and applied to continuous stage measurements recorded at 10 min intervals by either gas bubblers (Waterlog Model H-350 Lite and H-355, Design Analysis Associates Inc., Logan, UT, USA) connected to a Campbell Scientific CR10X datalogger (Logan, UT, USA) or stand-alone pressure transducers (HOBO U20, model U20-001-01, Onset Computer Corporation, Pocasset, MA, USA). The accuracy of different stream level sensors is within 0.1 cm (Table 3). Due to the potential for high flows to cause changes in the shape of control sections, new stage-discharge relationships were derived annually and after flood events for each stream. Coefficients of determination for stage-discharge relationships ranged from 0.72 to 0.99, with 75% of the relationships being higher than 0.90. To normalize Q across catchments, volumetric discharges (m^3 s^{-1}) were converted to area-depths (mm day^{-1}) using the gross catchment drainage. Catchment areas were derived from 1 m resolution digital elevation models generated from aircraft based LiDAR techniques.

2.2.4. Baseflow

The baseflow component of the continuous daily Q record from each stream was separated using a recursive digital filtering method which partitions baseflow (lower frequency signal) from quickflow (higher frequency signal) (Nathan and McMahon, 1990). The recursive digital filter applies a three pass filter to daily Q, and each pass produces less baseflow as a percentage of quickflow. This technique is objective, repeatable, automated, and considered more stable than other baseflow separation methods (Nathan and McMahon, 1990). For the present study, a two pass filter was applied to the data because it is recommended that the fraction of water yield contributed by baseflow should fall between the first and second pass (Arnold and Allen, 1999; Arnold et al., 1995).

2.2.5. Electrical conductivity (EC)

Water quality monitoring was conducted simultaneously with streamflow measurements at each site throughout the study period. Manual depth integrated samples were collected in 1 L acid washed (10% HCl) and triple rinsed, high density polyethylene brown bottles. Samples were stored in a cooler or refrigerator at 4 °C and subsequently analyzed within four days after collection. EC (μS cm^{-1}) was determined in the laboratory using a Man-Tech PC Autotitrator with conductivity probe (Man-Tech Associates Inc, Gulph, ON, Canada). EC was sampled as baseline water quality parameter during the study period. In the context of this study, EC was used to investigate the influence of groundwater and support baseflow separation methods between treatments.

2.2.6. Flow weighted stream temperature

To more clearly interpret the differences in stream temperatures between treatments, the weighted average of daily stream temperatures was normalized by mean daily discharge using the following:

$$To_v = \sum_{i=1}^{365} To_i Q_t \bigg/ \sum_{i=1}^{365} Q_t \qquad (1)$$

where To_i is the mean daily water temperature for the ith day (°C), Q_t is the mean daily discharge for the ith day ($m^3\ s^{-1}$), and To_v is the flow weighted mean annual water temperature (°C) (Pekarova et al., 2008).

2.3. Statistical analyses

Most variables were not normally distributed by examining Q–Q plots. As a result, descriptive statistics using measures of central tendency (means and standard deviation) were only applied to describe temporal and spatial trends of the data and to serve as a comparison between treatments. To test for significant differences between treatments, non-parametric statistical analyses were applied. The Kolmogorov–Smirnov test of equality of empirical cumulative distribution functions (ECDFs) was used to determine differences between treatments for stream temperature, air temperature, discharge, baseflow, and flow weighted mean daily water temperature. ECDFs are ‘empirical’ in nature, so their shape is related to the distribution of sampled data. Two-sided K–S tests were completed for each variable across the three catchment groups. The null hypothesis was that sample distributions were equal across treatments ($\alpha = 0.05$).

Temperature duration curves (TDC) were calculated to examine the variability in mean daily T_s by showing the relationship between T_s in each treatment and the percentage of time it was exceeded. Stream TDCs were produced by ranking T_s in descending order and assigning each value a probability of exceedance using the Weibull formula (Chow et al., 1988).

The rank-based, non-parametric Mann–Kendall (MK) statistical test was used for trend detection in the T_s time series (2004–2010) for each “treatment”. The lag-one serial correlation coefficient was statistically significant ($\alpha = 0.05$, $r = 0.97$) for the unburned, burned, and salvage logged catchments. Accordingly, autocorrelation, which leads to potentially inaccurate assessments of the significance of a trend, was identified. Thus, prior to the MK test for trend, serial correlation was removed from the T_s time series by pre-whitening the data (Yue et al., 2002).

All statistical analyses and graphics were completed using *R* version 2.15.2 (R Core Team, 2012) and SigmaPlot version 11.2.0.5 (Systat Software Inc., 2008).

3. Results

3.1. Effects of wildfire and post-fire salvage logging on stream temperature

The mean daily stream temperature (T_s) and standard error in unburned catchments (2.8 ± 0.04 °C) was lower than in the burned (3.6 ± 0.04 °C) and salvage logged catchments (4.9 ± 0.09 °C) for the period of record (Fig. 2). There were significant differences (Kolmogorov–Smirnov (K–S) test) in mean daily T_s between unburned catchments and both the burned ($D = 0.219$, $p < 0.001$) and salvage logged catchments ($D = 0.266$, $p < 0.001$). Mean daily T_s in the burned catchments also differed significantly from T_s in the salvage logged catchments ($D = 0.304$, $p < 0.001$). A higher critical value (D) indicates that differences in mean daily T_s were statistically greatest between burned and salvage logged streams. Weighting mean annual T_s by flow (To_v) produced slight shifts in this trend (where unburned [3.4 ± 0.2 °C] < salvage logged [4.0 ± 0.5 °C] < burned [4.1 ± 0.1 °C]). The Mann–Kendall (MK) test results indicated that there was little recovery (return to pre-disturbance levels) in mean seasonal (May–October) T_s over a period of seven years post-fire in the burned or salvage logged catchments (Fig. 3). Kendall’s tau (measure of the degree of concordance between two groups of ranked data) was −0.006 in the unburned catchments ($p = 0.74$), −0.0008 in the burned catchments ($p = 0.96$), and −0.022 in the salvage logged catchments ($p = 0.28$).

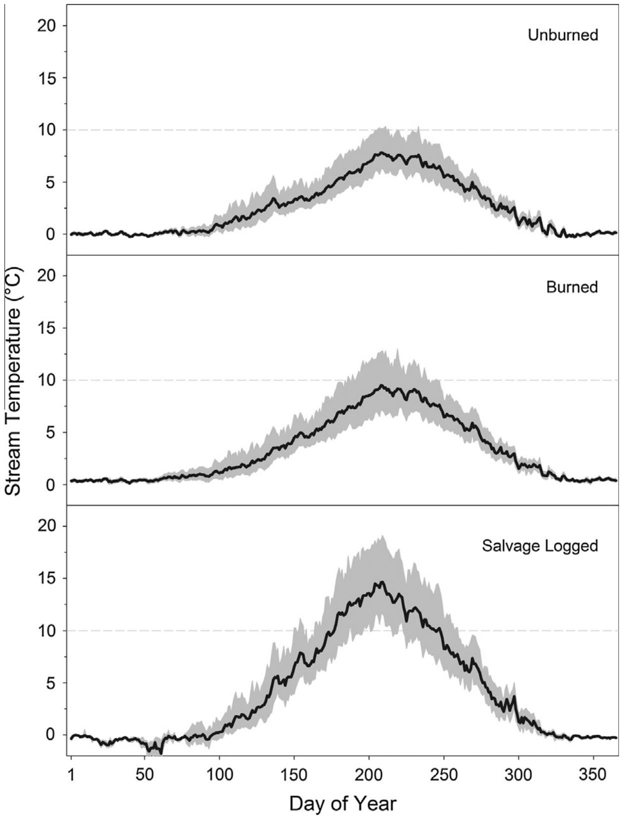

Fig. 2. Mean, minimum, and maximum daily T_s (2004–2010) for unburned, burned, and salvage logged catchments. The upper and lower boundary of the shaded area in each plot indicates the maximum and minimum daily T_s. The solid line denotes the mean daily T_s recorded for each treatment.

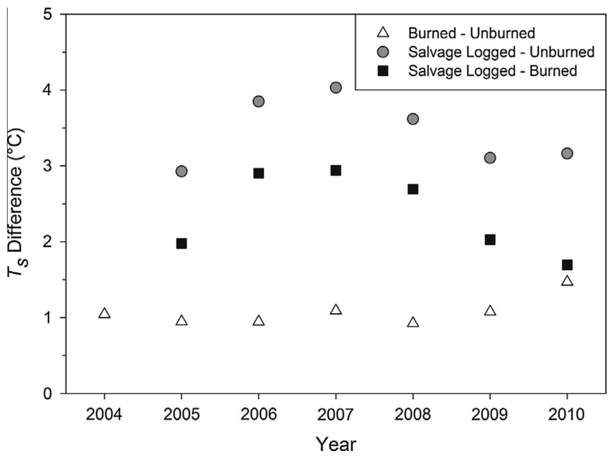

Fig. 3. Difference in mean seasonal T_s (May–October) between burned and unburned, post-fire salvage logged and unburned, and post-fire salvage logged and burned catchments from 2004 to 2010.

Average maximum daily T_s in unburned catchments (3.8 ± 0.06 °C) were lower than in the burned (4.8 ± 0.05 °C) and post-fire salvage logged catchments (6.9 ± 0.11 °C). The K–S tests indicated maximum T_s was significantly different between unburned vs. burned ($D = 0.206$, $p < 0.001$), unburned vs. salvage logged ($D = 0.267$, $p < 0.001$) and burned vs. salvage logged catchments ($D = 0.271$, $p < 0.001$). Maximum daily T_s exceeded 20 °C on 51 days in the burned streams and on 146 days in the post-fire salvage logged streams. However, the maximum daily T_s increased to 17.5 °C only once in the unburned streams. Maximum annual T_s followed a similar pattern and lower temperatures were observed in unburned catchments (11.8 ± 0.5 °C) compared to burned (15.7 ± 0.9 °C) and post-fire salvage logged catchments (21.5 ± 1.1 °C).

Minimum daily T_s during the ice-free periods (May–September) were lower in unburned catchments (4.0 ± 0.04 °C) than in burned (4.9 ± 0.04 °C) and post-fire salvage logged catchments (6.8 ± 0.08 °C). The minimum T_s was significantly different (K–S test) during the ice-free periods between unburned vs. burned ($D = 0.210$, $p < 0.001$), unburned vs. salvage logged ($D = 0.511$, $p < 0.001$) and burned vs. salvage logged catchments ($D = 0.380$, $p < 0.001$).

Short and long term temporal variation in T_s was pronounced within individual days (diel), years, and for the period of record. The results followed similar trends with salvage logged > burned > unburned catchments. Average diel variability in T_s was most pronounced in salvage logged catchments (3.5 ± 0.05 °C), followed by burned (2.2 ± 0.03 °C) and unburned catchments (1.9 ± 0.03 °C) (Fig. 4). While the differences in diel T_s between the unburned, burned, and post-fire salvage logged streams appeared to be marginal, these differences were statistically significant in comparisons between unburned vs. burned ($D = 0.103$, $p < 0.001$), burned vs. post-fire salvage logged ($D = 0.179$, $p < 0.001$), and unburned vs. post-fire salvage logged catchments ($D = 0.273$, $p < 0.001$).

The highest mean annual standard deviation (s) in T_s was observed in the salvage logged catchments ($s = 5.2$ °C) while the variability was lower in the burned ($s = 3.3$ °C) and unburned catchments ($s = 2.8$ °C). Moreover, the median absolute deviations of T_s within years (a more robust metric against the presence of outliers), were also greatest in the salvage logged catchments (5.4 °C) followed by the unburned (3.7 °C) and burned catchments (3.2 °C).

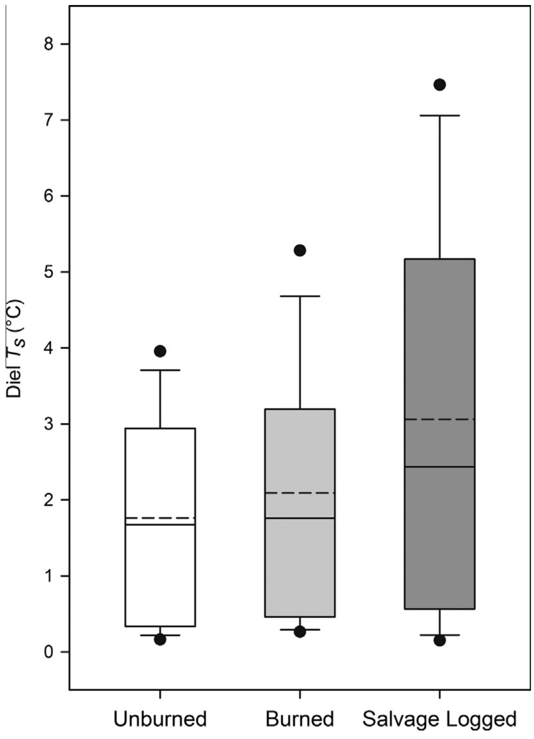

Fig. 4. Distribution of daily diel T_s in unburned, burned, and post-fire salvage logged catchments. Solid lines within boxplots denote the median (50th percentile), dashed lines denote the mean, outer edges of the boxplot indicate the 25th and 75th percentile, whiskers represent the 10th and 90th percentiles, and upper and lower dots denote 5th and 95th percentiles.

For the period of record, the stream temperature duration curves (TDC) showed that T_s in the wildfire impacted streams were most variable (Fig. 5). Similar to streamflow based duration curves, a steeper TDC slope is more indicative of greater variability. The observed pattern in slopes of TDC were: salvage logged > burned > unburned T_s.

3.2. Drivers of stream temperature

The relationship between mean weekly T_s and mean weekly T_a was non-linear in all catchments, resembling an S-shaped (sigmoid) function (Fig. 6) (Mohseni and Stefan, 1999). At air temperatures <0 °C the mean weekly stream temperature was stable at approximately 0 °C. At moderate air temperatures, T_s and T_a were linearly proportional (slope of the T_s/T_a relationship near 1:1), while at high air temperatures the slope of the T_s/T_a relationship appeared asymptotic.

T_s most closely tracked T_a in the salvaged logged catchments (Fig. 7c). Alternatively, T_s did not track T_a as closely in the unburned (Fig. 7a) and burned catchments (Fig. 7b). Seasonal patterns of hysteresis between mean monthly T_a and T_s were most evident in unburned and burned catchments (Fig. 7). In the unburned and burned catchments T_s was noticeably lower during the spring and early summer months (April–June) when T_a was rising, when compared to T_s during the late summer and autumn months (August–October) when T_a was generally decreasing. In the unburned and burned catchments, maximum monthly T_a was generally observed in July (unburned: 15.0 °C; burned 15.1 °C), but mean monthly T_s peaked in August in the unburned (7.1 °C) and burned catchments (8.5 °C). Alternatively, in the salvage logged catchments, both maximum monthly T_a (15.0 °C) and maximum monthly T_s (13.2 °C) occurred in July. In general, mean daily T_a was the same between catchment groups with observations of 3.1 ± 0.1 °C in unburned catchments and 3.0 ± 0.1 °C in the burned catchments. The range of T_a was slightly lower in unburned catchments (56.0 °C) compared to the burned catchments (57.4 °C). Comparison of ECDF's for mean

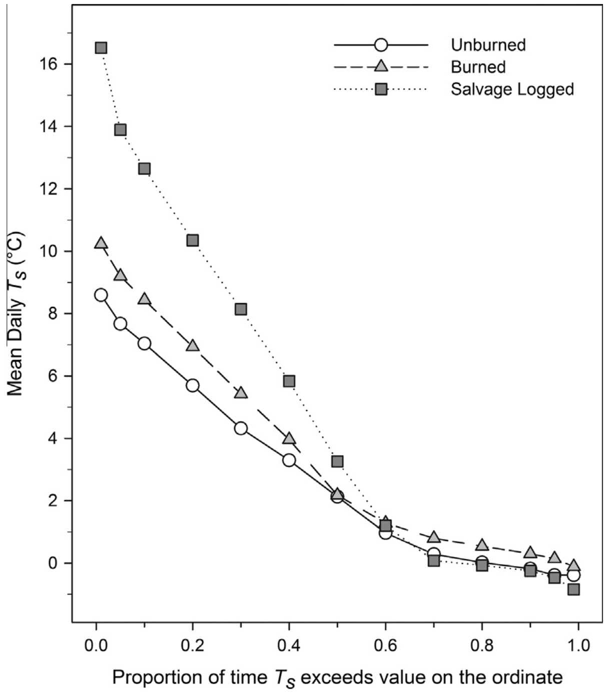

Fig. 5. Stream temperature duration curves for unburned, burned, and post-fire salvage logged catchments.

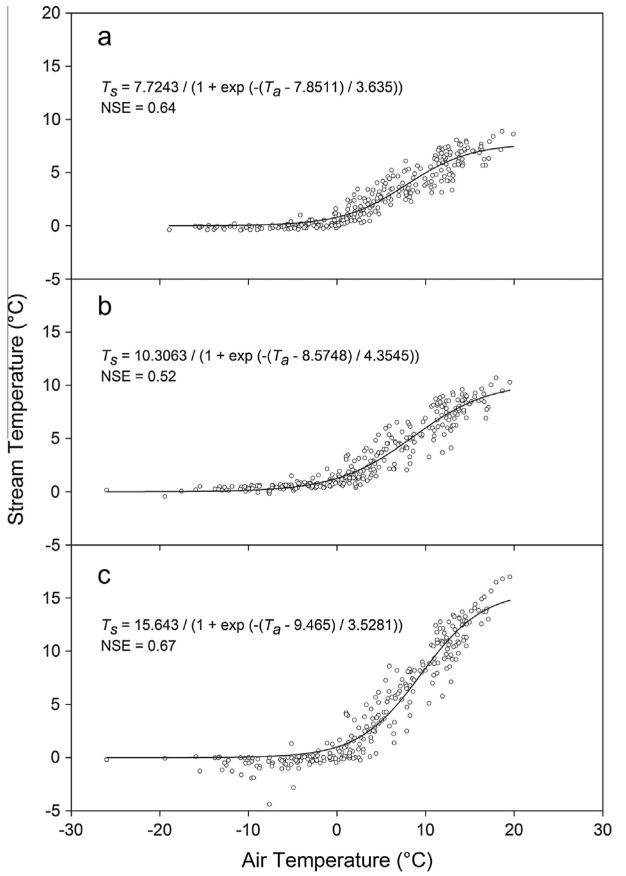

Fig. 6. Relationship between weekly T_s and weekly T_a (2005–2010) in the (a) unburned, (b) burned, and (c) burned and salvage logged catchments. NSE: Nash–Sutcliffe efficiency coefficient.

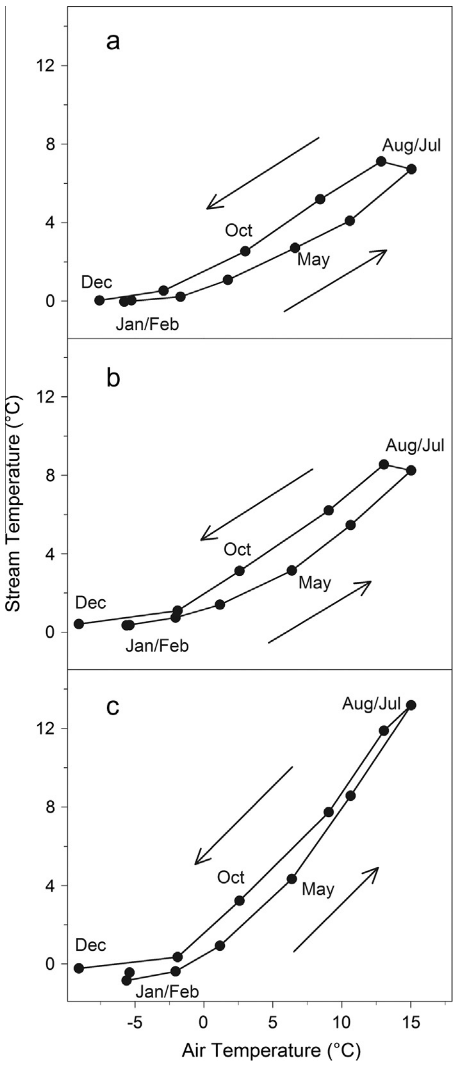

Fig. 7. Seasonal patterns of hysteresis between mean monthly T_a and T_s (2005–2010) for (a) unburned, (b) burned, and (c) salvage logged catchments.

daily T_a using K–S tests were not found to be significantly different between catchments groups ($D = 0.026$, $p = 0.46$).

Annual trends in the differences in mean seasonal (May–October) T_s among catchments showed dissimilar sensitivity to annual variation in mean T_a (Figs. 3 and 6). The largest differences in mean seasonal T_s among catchment groups (particularly between the post-fire salvage logged catchments and both the unburned and burned catchments) was evident in 2006 and 2007 which was coincident with the years of highest mean daily T_a and solar insolation. This pattern was not observed in the difference in mean T_s between the burned and unburned catchments; rather, the difference in mean annual T_s remained relatively constant over the study period for these catchment groups (Fig. 3).

Advective energy exchanges were also associated with variation in T_s among catchment groups. Mean daily discharge (Q) was highest in burned catchments (2.2 ± 0.04 mm d^{-1}), followed by unburned (1.9 ± 0.03 mm d^{-1}), and post-fire salvage logged catchments (1.4 ± 0.04 mm d^{-1}) during the study period (Fig. 8). Variation (standard deviation) of mean daily Q was also greater in the burned (3.1 mm d^{-1}) but similar in both unburned and post-fire salvage logged (2.4 mm d^{-1}) catchments. K–S tests indicated that mean daily Q was significantly different between unburned and burned ($D = 0.169$, $p < 0.001$) and unburned and salvage logged ($D = 0.279$, $p < 0.001$) catchment groups. The largest differences in Q were observed between burned and post-fire salvage logged catchments ($D = 0.433$, $p < 0.001$). This pattern (burned > unburned > salvage logged) was also evident in mean annual Q among catchment groups (Table 2).

The temporal distribution of Q across all treatments was typical of snowmelt dominated (nival) regimes. However, differences were observed in both the timing and magnitude of Q among the catchment groups. The mean timing of onset of spring melt occurred earlier in the salvage logged catchments and was more variable (Day of Year (DOY): 106 ± 4.8 days). This was followed by the burned (DOY: 129 ± 2.3 days) and unburned catchments (DOY: 130 ± 2.9 days). However, the mean magnitude of the peak snowmelt freshet discharge was lowest in the salvage logged catchments (2.4 mm ± 0.9), and greater in the unburned (3.2 mm ± 1.2), and burned catchments (5.5 mm ± 1.9).

The mean fraction of total Q contributed by baseflow was lowest in the post-fire salvage logged catchments (~55%), with increasing baseflows observed in the burned (~70%) and unburned (~71%) catchments. K–S tests show these differences in baseflow contributions among catchment groups were significant between unburned vs. burned ($D = 0.210$, $p < 0.001$), unburned vs. post-fire salvage logged ($D = 0.299$, $p < 0.001$), and burned vs. salvage logged catchments ($D = 0.450$, $p < 0.001$). Variation in electrical conductivity (EC) was consistent with the pattern among catchment groups from the baseflow separation. Mean annual EC was lowest in the salvage logged catchments (190.6 ± 4.0 µs cm^{-1}), intermediate in the burned catchments (255.1 ± 2.6 µs cm^{-1}), and greatest in the unburned catchments (283.0 ± 2.5 µs cm^{-1}). Accordingly, the trend of increasing EC was also consistent with a gradient of increasing

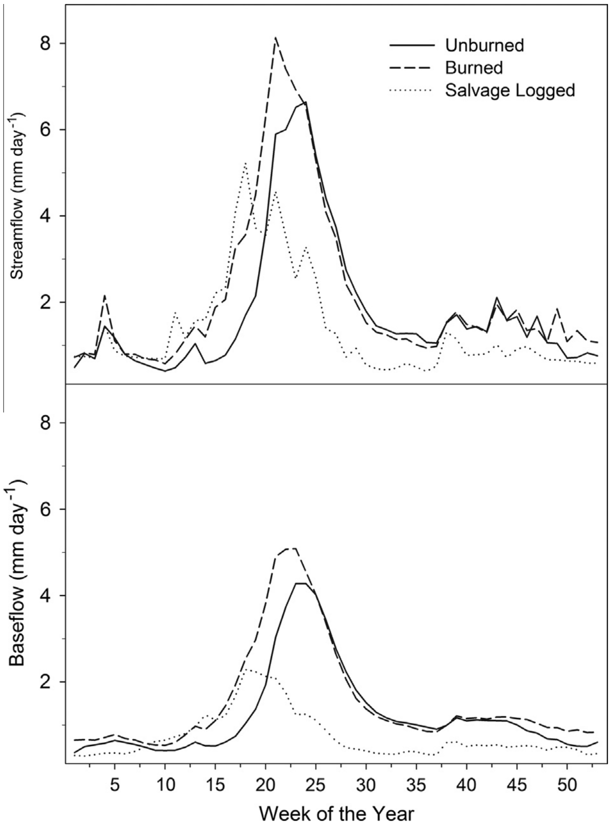

Fig. 8. Mean weekly streamflow and baseflow (2004–2010) in the unburned, burned, and salvage logged catchments.

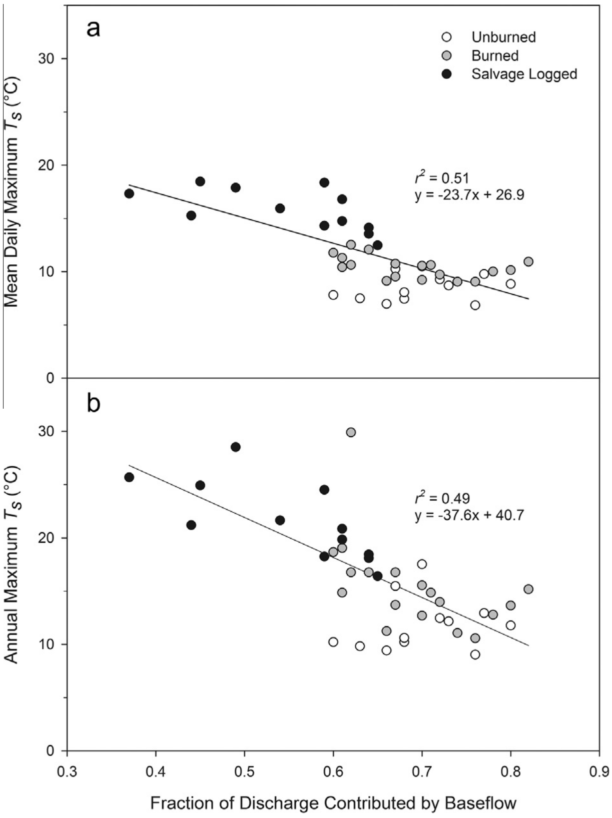

Fig. 9. Relationship between (a) mean daily maximum T_s and fraction of total Q contributed by baseflow, and (b) annual maximum T_s and fraction of total Q contributed by baseflow, in unburned, burned, and post-fire salvage logged catchments.

dominance of groundwater contributions to Q from post-fire salvage logged < burned and unburned catchment groups.

The relationships between the mean daily maximum T_s (average of the warmest T_s recorded each day of the year; Fig. 9a) and annual maxima T_s (warmest individual day within each year; Fig. 9b) with fraction of total Q contributed by baseflow showed clear association of greater T_s with lower fraction of baseflow in the post-fire salvage logged catchment group compared to burned and unburned catchment groups. While there was moderate variability in these relationships across the study period, annual variation in the fraction contributed by baseflow explained 51% of the variation in mean daily maximum T_s ($p < 0.001$) and 49% of the variation in annual maximum T_s among catchment groups from 2004 to 2010 ($p < 0.001$).

4. Discussion

4.1. Stream temperature response to forest fire

The 2003 Lost Creek wildfire produced numerous long-lasting effects on the hydrology and water quality of the impacted catchments (Silins et al., 2014, 2009b). These impacts also include increases in stream temperature (T_s). Compared to the unburned streams, mean annual T_s was elevated 0.8–2.1 °C (individual years range: 0.6–3.8 °C) in the burned and post-fire salvage logged streams (Fig. 2). The observed temperature increases are comparable to those in similar hydro-climatic settings elsewhere. For example, wildfires in Rocky Mountain catchments in the Boise River basin (Idaho, USA) caused mean T_s to increase 3.7 °C in wildfire affected streams for seven years (Dunham et al., 2007) and in another study were <1.0 °C warmer compared to reference streams (Isaak et al., 2010). Following the high severity Hayman fire (Colorado, USA), average stream temperatures in burned catchments were 4.0 °C higher in the summer and 4.5 °C higher in the spring compared to stream temperatures in unburned catchments (Rhoades et al., 2011).

The mean daily maximum T_s across the seven post-fire years was also consistently warmer (1.0–3.0 °C) in the disturbed catchments compared to the unburned catchments. However, our data reflect the lower range of previously reported stream temperature measurement in catchments impacted by forest fire. In several US states impacted by forest fires (Colorado, Oregon, Washington State, Idaho, and Montana) maximum T_s in burned streams exceeded unburned streams by 1.4–10 °C (Amaranthus et al., 1989; Burton, 2005; Dunham et al., 2007; Mahlum et al., 2011; Rhoades et al., 2011; Woodsmith et al., 2004).

The effects of the wildfire on mean daily maximum T_s following the Lost Creek fire may have been muted compared to previous research due to several factors, including substantial groundwater contributions and hyporheic exchange in the study catchments (Figs. 8 and 9), which can buffer stream temperature patterns (Leach and Moore, 2011; MacDonald et al., 2014). Catchment and channel slopes were also steep (Table 2), which can increase streamflow and result in lower rates of warming of stream water (Tague et al., 2007). Additional factors, such as lower insolation associated with the higher latitude of the study area, higher site elevation, or differences in channel morphology (e.g., narrow, incised channels vs. wide channels) could have also contributed to the smaller effect of wildfire on T_s compared to other studies. Despite lower average peak T_s, summer water temperatures regularly exceeded 20 °C in the burned and post-fire salvage logged catchments but generally remained <15 °C in the unburned catchments.

Owing to the high severity of the fire, forest tree regeneration (early establishment and juvenile growth) in the higher elevation forests of this region has been slow, which has contributed to the slow recovery of T_s in the catchments burned by the Lost Creek fire. Trend analysis showed no significant decreases in T_s in the disturbed catchments during the seven years of study, suggesting that the effects on T_s from high intensity, high severity wildfires may be long lasting (Fig. 3). While there are few reports of long-term stream temperature trends in wildfire impacted catchments, observations from the Cottonwood Creek fire in Idaho (Dunham et al., 2007) and the Hayman fire in Colorado (Rhoades et al., 2011) support the likelihood that recovery of stream temperature regimes to pre-disturbance conditions may take decades in northern Rocky Mountain regions.

Changes in post-fire stream temperature can occur when shading from over-story vegetation is reduced which increases radiation inputs to the stream surface (Isaak et al., 2010; Johnson, 2004; Moore et al., 2005). While air temperature (T_a) is not generally a direct controlling factor on T_s (Johnson, 2003), it is often considered a surrogate or index of energy input. The relationship between T_a and T_s in the burned and unburned catchments of this study suggests that radiation may be an important control on T_s (Fig. 6) (Mohseni and Stefan, 1999). In the same research catchments, Burles and Boon (2011) concluded that complete removal of the forest canopy by the Lost Creek fire increased the incident radiation at the surface, which would have increased the energy availability for stream heating. Burles and Boon (2011) also showed that the lack of forest canopy and lower residual tree densities in burned areas resulted in a greater canopy transmissivity of shortwave radiation to the forest understory, whereas more incoming shortwave radiation was absorbed by the forest canopy in unburned areas. Additionally, the lower albedo of the blackened trees in burned areas relative to stems in unburned areas would absorb more radiative energy from incoming shortwave radiation, resulting in greater longwave radiation emitted to the stream surface. The net effect of greater incident shortwave (direct and diffuse) and longwave radiation at the stream surface would drive increased energy absorption for stream heating (Evans et al., 1998).

4.2. Interpreting the stream temperature response to salvage logging

An initial examination of T_s data from the Lost Creek fire suggested that secondary disturbance of post-fire salvage logging further increased T_s over that of fire alone (Figs. 2–4). However, this interpretation is confounded by several catchment-scale differences that influence T_s response to disturbance. For example, the area weighted catchment slope in the burned catchments was 7.7° steeper and the average stream slopes in the burned catchments were ~2° steeper than in the salvage logged catchment. Accordingly, greater hydraulic gradients in the burned catchments would have a strong influence producing increased water velocities, discharge rates, and hyporheic exchange (Table 2 and Fig. 8) (Kasahara and Wondzell, 2003). Streams with greater flow volumes tend to warm more slowly, because they typically have lower width-to-depth ratios and lower radiation input per volume (Tague et al., 2007). Thus, compared to salvage logged catchments, the effects of the canopy disturbance in the burned catchments would have been buffered because of higher stream discharges which are often negatively correlated with stream temperatures (Amaranthus et al., 1989; Constantz, 1998; Moore et al., 2005).

Stream temperatures in the burned catchment group may have also been affected by slight differences in average elevation which was ~195 m higher than the salvage logged catchments. Minor elevation effects (lapse rates) on T_a and precipitation inputs (Table 2) may have influenced the observed differences in T_s of the burned and post-fire salvage logged catchment groups (Table 2). However, much larger differences in hydro-climatic factors regulating T_s existed between disturbed (burned and post-fire salvage logged) and unburned catchments. Burles and Boon (2011) observed peak snow water equivalent (SWE) ~50–58% greater in the burned catchments compared to the unburned catchments due to decreased snow interception in burned areas and MacDonald et al. (2014) showed that snowmelt recharge of shallow groundwater can have significant dampening effects on summer stream temperatures in the study region. Snowmelt associated cooling of shallow groundwater and subsequent regulation of early summer T_s were likely less important in the salvage logged catchments because of both less snow accumulation (compared to the burned catchments) combined with lower baseflow (groundwater) contributions to streamflow in these catchments (Fig. 8). Moreover, the average timing of onset of the snowmelt freshet occurred approximately 20–24 days later in the burned and unburned catchment groups compared to the salvage logged catchment groups (Fig. 8). The net result of differences in snowmelt timing was greater synchroneity between periods of peak discharge with greater insolation in the burned and unburned catchment groups compared to the salvage logged catchment groups where discharge was declining by that time. Because of the magnitude and timing of cold water inputs into the streams in burned catchments, the effects of the fire on T_s were likely dampened, whereas inputs of relatively cold groundwater were likely much smaller in the post-fire salvage logged catchment group where T_s appeared to be more tightly coupled to atmospheric energy inputs (Fig. 7).

The differential effects of wildfire compared to the additional effects of salvage logging were difficult to discern. However, multiple lines of evidence indicate that some of the observed differences between catchments were likely due to differences in advective and non-advective controls on T_s. Baseflow separation, consistently higher electrical conductivity (EC), and observations of high overwinter streamflows suggest that the hydrology of the burned and unburned catchments were dominated by deeper, slower flowpaths relative to salvage logged catchments (Fig. 8). Moreover, the pattern of differences in mean seasonal T_s between the salvage logged catchments and other catchments were more tightly coupled with the seasonal pattern of T_a and insolation than those of the burned and unburned catchment groups (Fig. 3). An inverse relationship between baseflow contributions to stream discharge and annual maximum T_s (Fig. 9), a much steeper T_s duration curve in the salvage logged catchments (Fig. 5), and a steeper slope of T_s/T_a relationships (Fig. 6) indicates a more variable thermal regime in this catchment group with less dampening of T_s by groundwater inputs compared to the burned catchments (Mohseni and Stefan, 1999). In high elevation, snowmelt dominated catchments greater volumes of stable temperature groundwater during the ice free periods (May–September) can dampen stream temperatures (Leach and Moore, 2011; Poole and Berman, 2001). Stream temperature changes following the severe wildfires of 1988 in Yellowstone National Park were also very small due to the buffering effects from cool groundwater sources (Minshall et al., 1989). While a reach-scale study in an unburned catchment (Star Creek) provided evidence that advective energy exchange from groundwater discharge is an important control on T_s, particularly in the steeper catchments in the Flathead mountain range in this study (MacDonald et al., 2014), groundwater appeared to have less of a buffering effect on T_s in the salvage logged catchments. Accordingly, further study of the mechanisms that account for differences in the relative impacts of wildfire compared to the impact of post-fire salvage logging is required.

5. Conclusion

Seven years of water temperature measurements in burned, post-fire salvage logged, and reference catchments showed that severe wildfires can have extensive and prolonged impacts on the thermal regime of Rocky Mountain headwater streams. Mean annual T_s, mean daily maximum T_s, and mean daily minimum T_s were all warmer in streams draining burned and post-fire salvage logged catchments compared to streams in unburned catchments, and there was no evidence of recovery of T_s over seven years. While wildfire effects on stream thermal regimes observed in this study were lower than previously reported for Rocky Mountain catchments in more southerly latitudes, advective inputs of colder groundwater likely played a greater role in dampening the disturbance effects observed in this study. While the highest T_s were observed in the post-fire salvage logged catchment group, additional effects on T_s from the secondary disturbance of salvage harvesting remain uncertain because of likely differences in the physical mechanisms controlling T_s across catchments in this study. These findings highlight the need for studies investigating how physical controls after disturbance affect stream temperature across a range of hydro-climatic domains.

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