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Relative effects of climate change and wildfires on stream temperatures: a simulation modeling approach in a Rocky Mountain watershed

Lisa Holsinger · Robert E. Keane · Daniel J. Isaak · Lisa Eby · Michael K. Young

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Abstract Freshwater ecosystems are warming globally from the direct effects of climate change on air temperature and hydrology and the indirect effects on near-stream vegetation. In fire-prone landscapes, vegetative change may be especially rapid and cause significant local stream temperature increases but the importance of these increases relative to broader changes associated with air temperature and hydrology are not well understood. We linked a spatially explicit landscape fire and vegetation model (FireBGCv2) to an empirical regression equation that predicted daily stream temperatures to explore how climate change and its impacts on fire might affect stream thermal conditions across a partially forested, mountainous landscape in the western U.S. We used the model to understand the roles that wildfire and management actions such as fuel reduction and fire suppression could play in mitigating stream thermal responses to climate change. Results indicate that air temperature increases associated with future climates could account for a much larger proportion of stream temperature increases (as much as 90 % at a basin scale) than wildfire. Similarly, land management scenarios that limited wildfire prevalence had negligible effects on future stream temperature increases. These patterns emerged at broader spatial scales because wildfires typically affected only a subset of a stream's network. However, at finer spatial and temporal scales stream temperatures were sensitive to wildfire. Although wildfires will continue to cause local, short-term effects on stream temperatures, managers of aquatic systems may need to find other solutions to cope with the larger impact from climate change on future stream warming that involves adapting to the increases while developing broad strategies for riparian vegetation restoration.

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L. Holsinger (✉) · R. E. Keane
US Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT, USA
e-mail: lisamholsinger@fs.fed.us

D. J. Isaak
US Forest Service, Rocky Mountain Research Station, Boise Aquatic Sciences Laboratory, Boise, ID, USA

L. Eby
College of Forestry and Conservation, University of Montana, Missoula, MT, USA

M. K. Young
US Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory, Missoula, MT, USA

1 Introduction

Aquatic ecosystems are warming due to climate change (Isaak et al. 2012; Schneider and Simon 2010; Webb and Nobilis 2007) and are predicted to continue warming this century (Ficklin et al. 2013; Mantua et al. 2009; Mohseni et al. 2003; van Vliet et al. 2013). Global circulation models project global mean air temperatures increases from 1.1 to 6.4 °C over the next century (Bates et al. 2008; Houghton et al. 2001). This will cause warming of aquatic environments through sensible heat transfer, long-wave atmospheric radiation, and ground and surface water heating (Gunawardhana and Kazama 2011; Webb et al. 2008). Changes in streamflow runoff and timing due to earlier snowmelt (Hidalgo et al. 2009), shifts in precipitation from snow to rain (Knowles et al. 2006), diminished seasonal snowpack (Barnett et al. 2008), and reduced orographic precipitation enhancement (Luce et al. 2013) may also affect stream temperatures (Isaak et al. 2012; Leach and Moore 2013; Luce et al., in press).

Global warming may also indirectly affect stream temperatures by changing riparian vegetation that provides shade along streams (Amaranthus et al. 1989; Dwire and Kauffman 2003; Dunham et al. 2007). Such vegetative alterations are occurring globally as terrestrial ecosystems adapt to changing drought and heat stress (Allen et al. 2010) and increased wildfire activity. Fire-prone landscapes in particular are anticipated to experience rapid and substantial shifts in wildfire across areas in the western US, Mediterranean, Australia (Moritz et al. 2012), South America, central Asia, and northern Africa (Kloster et al. 2011).

Wildfires may have dramatic effects on vegetation in riparian areas, and concomitant increases in stream temperatures are well documented. At small spatial scales (site to stream scale), these temperature increases may be large (e.g., > 2.0 °C) but the amount of change varies depending on fire severity and local context (Dunham et al. 2007; Hall and Lombardozzi 2008; Mahlum et al. 2011; Minshall et al. 1997; Rhoades et al. 2011; Sestrich et al. 2011). Less research has focused on the importance of wildfire-induced stream temperature increases at river network scales, but some evidence suggests wildfire effects are smaller when viewed more broadly (Isaak et al. 2010). Resolving this apparent discrepancy is important because wildfire suppression and fuel treatment programs are sometimes proposed to offset the effects of climate warming on sensitive aquatic species which can be expensive to implement (Luce et al. 2013).

Here, we evaluate how thermal characteristics of streams across a mountain basin in the western US might be influenced at local- and network-scales by climate change and wildfire management. To accomplish this goal, a spatially-explicit, process-based ecosystem model (Keane et al. 2011) was used to simulate fire and forest dynamics under climate change scenarios. Outputs from that model were linked to an empirical stream temperature model developed from local monitoring data. This linked model system was used to assess the influence of a warming climate on fire regimes and their synergistic effect on stream temperatures at a variety of spatial scales, and to assess the effectiveness of fire management strategies at reducing future stream warming.

2 Methods

2.1 Study area

Our study area is the East Fork Bitterroot River (EFBR) basin, a snowmelt-dominated, 105,487-ha watershed (elevations, 1,225–2,887 m) in west-central Montana, USA

(Fig. 1). The basin is mainly a forested landscape (80 %) dominated at lower elevations by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) and at high elevations by lodgepole pine (*Pinus contorta* var. *latifolia*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmanii*). This area has experienced recent fire (55,000 ha burned in 2000 and 4,000 ha in 2007) and has an extensive weather record (1956–present) and stream temperature (1993–present) datasets. Annual precipitation averages 41 cm (range, 26–57 cm) with most falling as snow from November to March. Flows peak in May and June as warming temperatures melt the snowpack. The area has primarily a mixed-severity historical fire regime (Arno et al. 2000) with short intervals between low-to-medium intensity fires (mean frequencies of 11–30 years) except in steep terrain, lower-subalpine, and north-facing slopes where stand-replacing fires can occur (Arno 1976). A variety of native fish inhabit the basin including westslope cutthroat trout (*Oncoryhnchus clarkii lewisi*), slimy sculpin (*Cottus cognatus*), mountain whitefish (*Prosopium williamsoni*) and longnose suckers (*Catostomus catostomus*), and the watershed is a core conservation area for bull trout (MBTSG 1995).

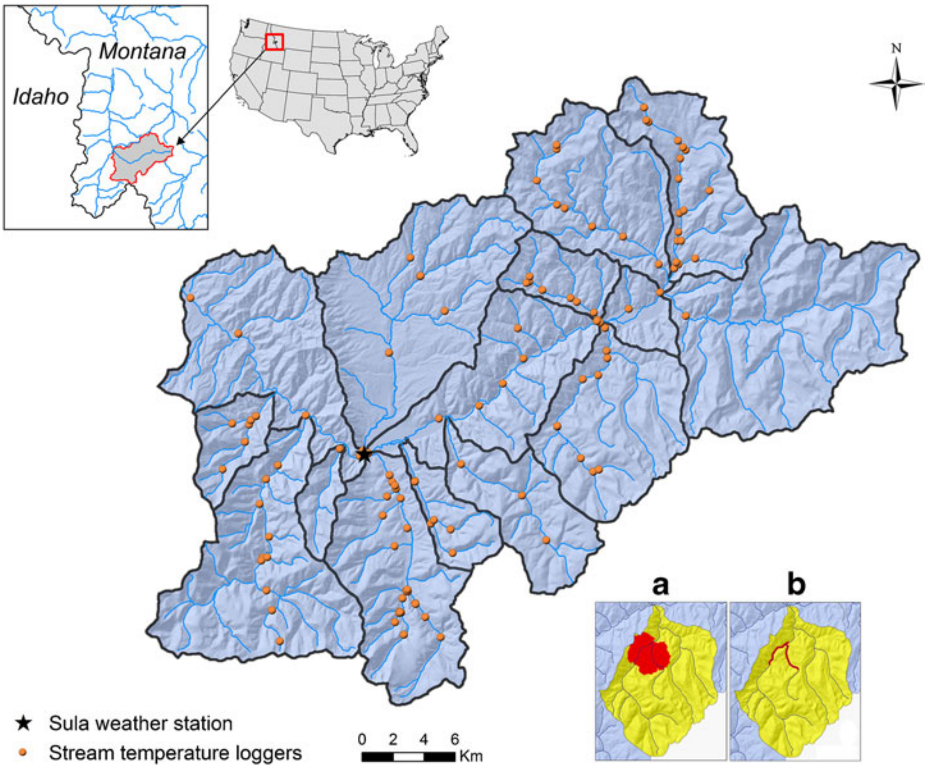


Fig. 1 Location of East Fork Bitterroot watershed study area with subwatersheds and major stream networks. Inserts *A* and *B* in lower right are examples in one subwatershed where stream temperature response to a wildfire was assessed at two finer spatial scales: (*A*) fire perimeter scale, where fire conditions were characterized across upland and riparian habitat (in *red*); and (*B*) riparian burn scale where fire conditions were evaluated within riparian habitat only (*red*)

2.2 Model description

2.2.1 FireBGCv2 landscape simulation model

Spatially explicit ecosystem landscape models can address questions about climate-induced changes in landscape pattern (Turner et al. 1995) and land management measures (Cushman et al. 2011) through integrating climatic influences on biogeochemical cycles, vegetation dynamics, disturbance regimes, and hydrologic processes (Littell et al. 2011). We used the landscape ecosystem process model FireBGCv2 which assimilates a mechanistic, individual tree succession model with a spatially explicit fire model to stochastically simulate fire ignition, spread, and its effects on ecosystem components (Keane et al. 2011). FireBGCv2 has been well described (Keane et al. 2011), and we present a brief synopsis as well as model inputs, calibration, and validation for the EFBR in Online Resource 1.

2.2.2 Stream temperature regression model

We assembled a 9-year stream temperature database (2001–2009) from 116 sites distributed widely throughout the EFBR based on monitoring conducted by the U.S. Forest Service (USFS), University of Montana, and the State of Montana (Fig. 1). We used data collected during the summer (June–September), the warmest and most thermally stressful period for most aquatic species, and summarized thermograph readings (typically taken at 0.5- to 2.0-h intervals) into daily maxima—a metric highly sensitive to radiation gains associated with loss of riparian shading (Dunham et al. 2007; Isaak et al. 2010).

Predictors for the stream temperature model included a combination of FireBGCv2-derived variables and topographic variables. We simulated FireBGCv2 for the period corresponding to the stream temperature field dataset, and output a suite of dynamic variables describing weather (e.g., air temperature, relative humidity, precipitation), vegetation (e.g., leaf area index, water potential of soil and leaves), ecosystem processes (e.g., evapotranspiration, soil temperature), and hydrologic conditions (e.g., stream discharge). Topographic characteristics (e.g., elevation, channel slope, drainage size) were also included since they often affect stream temperatures in montane landscapes (Isaak et al. 2010; Sloat et al. 2005). We linked the predictor variables to stream temperatures using a multiple regression model because it facilitated simultaneous assessment of the dynamic predictors from FireBGCv2 and topographic characteristics. The relationship between air temperature and stream temperature in the model was treated as a linear function because stream temperatures in the EFBR are colder than the range where nonlinearities occur (Mohseni and Stefan 1999). A global model with all predictors was initially fit and stepwise procedures were used to exclude non-significant predictors and to produce a final parsimonious model wherein all predictors were statistically significant at α<0.01. The equation describing the final model included three FireBGCv2 variables and three topographic features, as follows:

$$\begin{aligned} \textit{Daily maximum stream temperature} &\\ &= 13.9 + 0.527(T) - 0.255(F) + 0.0189(F*T) + 0.00574(SR) - 0.00703(Elv)\\ &\quad - 5.65(Slp) + 0.0000000016(CA) \end{aligned}$$

where T is daily average air temperature (°C), F is stream flow (m^3•sec $-^1$), SR is solar radiation penetrating the canopy to reach the stream surface (watts•m^{-2}), Elv is elevation (m), Slp is channel slope (drop over length), and CA is contributing area (m^2). An interaction term between air temperature and streamflow was included to account for short-term flow fluctuations that could affect stream temperature sensitivities to air temperature. The resulting stream temperature equation accounted for large portions of variability with good predictive accuracy (daily maximum r_s=0.84, MAE=1.70 °C, RMSE=2.21 °C), and validation results were reasonably accurate (Online Resource 2). We linked the stream temperature regression model to FireBGCv2 such that stream temperatures could be predicted for every 30-m pixel in the EFBR stream network at a daily time step in our simulations. We did not attempt to model stream temperatures using more complex statistical approaches that could account for spatial autocorrelation among temperature sites (Isaak et al. 2010, 2014) because their increased computational requirements would have precluded linkage to FireBGCv2 for simulations.

2.3 Simulation experiment

We used a 3×3 factorial design to evaluate the effects of two factors, climate and fire management, on stream temperature where each combination of factorial levels was considered a scenario (Online Resource 3). Three climate levels were simulated including: recent climate which we term historical (H), and A2 (hot, dry) and B2 (warm, wet) to represent potential conditions under future greenhouse gas emissions (Nakicenovic et al. 2000). The H scenario was built on a 55-year daily weather record (1956–2010) from the U.S. National Weather Service weather station at Sula (Fig. 1). We used the meteorological model Mountain Climate (Thornton and Running 1999) to extrapolate the weather record of daily temperature (minimum, maximum), precipitation, humidity, and radiation to sites across the EFBR by correcting for elevation, slope, aspect, and lapse rates. To simulate A2 and B2 climates, we supplied FireBGCv2 with adjustments to the historical weather for temperature, precipitation, and CO_2 levels using offset values relative to a 1950–1999 base period from the Hadley Centre (UK) HadCM3 general circulation model based on an average of grid points corresponding to the Pacific Northwest region (Mote 2003) from the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (Nakicenovic et al. 2000). Temperature and precipitation offsets were incrementally increased from present conditions to A2/B2 levels (depending on season, differential offsets were 2.5–6.7 °C in air temperature, 0.67–1.11 multiplier in precipitation for A2; 1.0–2.1 °C air temperature increase, 0.99–1.24 precipitation multiplier for B2; Mote 2003) over the first 100 years of simulations and then held at those levels for 300 years for a total of 400 simulation years. These temperature and precipitation offsets, under the A2 scenario, simulated declines in high elevation precipitation, increases in evapotranspiration, shifts in precipitation phase and streamflow timing, and the concomitant lower streamflows expected with climate change. Predictions for downward solar radiation, as incorporated in more recent climate model experiments (Snover et al. 2013), were not available for the Pacific Northwest at the time of this study, hence solar radiation dynamics in these simulations reflected canopy changes resulting from fire disturbance alone (Online Resource 1). For fire management, we modeled three types of policy approaches. As a baseline condition, we represented a fire regime without suppression (N, for no management) allowing all ignited fires to burn across the landscape. We simulated an intermediate management strategy to explore the effects of fuel treatments (F) allowing all ignitions to burn but implementing prescribed burning and thinning across 7 % of the landscape each year, a level considered effective for moderating fire behavior (Finney et al. 2007). The third level represented contemporary fire suppression (S) where 90 % of ignited fires were extinguished. We ran model simulations at daily time steps, and replicated each scenario ten times to create long-term time series which captured the climate change signal and extreme wildfire events.

2.4 Analyses

2.4.1 Fire regime characteristics

We evaluated climate and fire management effects on fire regimes using a generalized linear mixed model (GLMM) approach and two-way ANOVAs. We tested for significant differences in three variables describing fire effects: fire size (ha), biomass consumed by fire (kg • m^{-2}) as a proxy for severity (Keeley 2009), and frequency (number of fires per year). We used a SAS GLIMMIX procedure to evaluate the first two fire variables, with climate and fire management factors as the main treatment effects, and using repeated measures across replicates and years ($n \approx 4{,}000$), accounting for temporal correlation with a radial smoother (McCarter and Burris 2010). To analyze fire frequency, we conducted a two-way ANOVA because data were summarized by replicate and therefore had fewer samples ($n = 10$). Multiple comparisons for fire characteristics were also conducted (Online Resource 4). Finally, we examined how the interplay of fire and vegetation processes affected solar radiation incident on streams using a two-way ANOVA comparing solar radiation along stream networks across replicates ($n = 10$).

2.4.2 Stream temperature

We assessed stream temperature response to climate and fire management also using a GLMM approach at three spatial scales – subwatershed (Fig. 1), inside fire perimeters, and within riparian burns (Fig. 1, inserts A, B) . We first summarized each year's average weekly maximum temperature (AveWMT) from 7-day running averages of daily temperatures, and then calculated weighted means of AveWMT at each spatial scale across the appropriate 30-m stream pixels for each simulation year. Akaike Information Criterion (AIC) scores (Burnham and Anderson 1998) were used to identify treatment and covariates of the top fixed-effect model with their interactions for each spatial scale (Online Resource 5) from an a priori candidate list that included climate and fire management factors, and two fire covariates describing severity and amount of area burned. We then tested for significant differences in the top model with the GLMM using repeated measures across replicates and years ($n \approx 4{,}000$) and a radial smoother to account for temporal and spatial correlations; we present results for the Type III tests of fixed effects. At the subwatershed scale, the response variable was AveWMT, whereas at the fire-perimeter and riparian-burn scales we assessed stream temperature change comparing 1 year before to 1 year after each individual fire to evaluate the greatest possible effects from fire over short periods. At the two finer spatial scales, we limited our post-fire time frame to the first year after fire since the largest effect on the riparian canopy would most likely occur in that year. We also narrowed the scope of fire management to two strategies–no management and suppression–eliminating fuel treatment since analyses at the subwatershed scale indicated its fire regime was similar to no-management. Finally, multiple comparisons across climates were conducted at each spatial scale (Online Resource 4).

We also assessed the relative importance of the dynamic predictors (i.e., air temperature, solar radiation, and stream flow) to changes in AveWMT with climate warming and fire management using a sensitivity analysis approach. We included two spatial scales of analysis, basin-wide and within fires, to evaluate stream temperature sensitivity at the broadest and finest scales. At the basin scale, we evaluated which drivers most affected stream temperatures changes from historical to A2/B2 climates. The effects of each predictor were isolated by holding values for two predictors at their historical values (averaged across replicates and years for the basin) and changed the value of the third predictor to its value with climate change (B2, A2), and repeated the process for each predictor, comparing within fire management strategy. At the fire scale, we took a different approach—holding input values for two dynamic predictors at their pre-fire values and changing the value of the third predictor to its post-fire value, and repeating the process for each predictor, across all three climates and two fire management scenarios.

3 Results

3.1 Climate and fire management effects on fire regime and solar radiation

Fire regimes were significantly different across all climates and most fire management strategies and in their interactions (Table 1). As climates warmed, fires became larger and more frequent (Fig. 2a–c), and in the A2 scenario, severity decreased. Suppression decreased fire frequency but increased severity compared to no-management and fuel treatment approaches. The effect of fuel treatment was similar to the no-management strategy indicating that higher treatment levels were needed to alter fire regimes. Last, solar radiation incident on streams varied among climates, being highest under A2, lowest under B2, and intermediate in the historical climate; and suppression decreased solar radiation (Online Resource 4).

3.2 Climate and fire effects on stream temperature

Climate had the greatest impact on stream temperature across all three spatial scales in the GLMM analyses, while fire severity became more important at local scales. At the subwatershed scale, the top model included climate and fire management, both fire covariates, and all two-way interactions (Online Resource 5), with climate having the greatest influence on stream temperatures (*F*-value an order of magnitude larger than all other effects in Type III tests of fixed effects; Table 1). Stream temperature increases due to all factors were 5.0 °C higher in the A2 climate and 1.7 °C higher in the B2 compared to the historical climate (Fig. 2d; see Online Resource 2, Table 2 for summaries of dynamic predictor values). Both fire covariates significantly influenced stream temperature (Table 1), but their effect size was small. Increasing fire severity caused only nominal upward trends in stream temperatures in the historical and B2 climates and a slight cooling trend in the A2 climate; increasing proportions of area burned produced slight upward trends in stream temperature across all climates with the greatest in the A2 (Online Resource 6). At the fire perimeter scale, the top model included climate and fire management, one fire covariate (severity), and all two-way interactions (Online Resource 5), and climate and fire severity had the strongest influences on stream temperature change (similar *F*-values of 3.46 and 3.85, respectively; Table 1). Stream temperature changes after fire were small and not very different between climates with median increases of 0.2 to 0.3 °C across all climates (Online Resource 7). Fire severity nominally influenced stream temperatures where temperature increases following fire trended upward slightly with increasing severity–at most a 0.5 °C mean increase at the highest severity (Online Resource 7). Similarly, at the riparian burn scale, the top model included the same covariates with the addition of area burned (Online Resource 5), and climate and fire severity again had the greatest influences on stream temperature change (*F*-values of 4.13 and 5.59 respectively; Table 1). The level of effect from severity was relatively small with median stream temperature increases following fire between 0.3 to 0.4 °C across all climates and a slight trend towards greater temperature responses with increasing severity (Online Resource 7).

Similarly, sensitivity analyses indicated that air temperature was the main driver of stream temperature change but solar radiation changes became more important at a finer scale. At the basin scale, air temperature accounted for 90 % or more of stream thermal changes across all

Table 1 Results of generalized linear mixed models for the effects of climate and management on the biomass consumed by fire (kg m^{-2}), fire size (ha), stream AveWMT (average weekly maximum temperature) at the subwatershed scale, change (Δ) in AveWMT in the year prior compared to the year after fire at the scale of individual fire perimeters, and ΔAveWMT at the riparian burn scale

Type III tests of fixed effects

Effect	F	Degrees of freedom Numerator; denominator	*p*-value
Biomass consumed by fire			
Climate	100.72	2; 128	<0.0001
Fire management	134.48	2; 128	<0.0001
Climate*fire management	3.00	4;128	0.02
Fire size			
Climate	89.34	2; 188	<0.0001
Fire management	0.04	2; 188	0.97
Climate*fire management	0.99	4; 188	0.41
AveMWT at subwatershed scale			
Climate	687.94	2; 527	<0.0001
Fire management	2.39	2; 520	0.09
Climate*fire management	0.03	4; 385	0.99
Biomass consumed	14.55	1; 5,115	0.0001
Biomass consumed *climate	3.14	2; 5,247	0.04
Biomass consumed*fire management	1.14	2; 5,204	0.32
Percent burned	11.27	1; 5,011	0.0008
Percent burned*climate	6.59	2; 5,137	0.0014
Percent burned*fire management	0.94	2; 5,137	0.39
ΔAveMWT at fire perimeter scale			
Climate	3.46	2; 696	0.03
Fire management	1.03	1; 857	0.31
Climate * fire management	0.22	2; 667	0.80
Biomass consumed	3.85	1; 894	0.05
Biomass consumed*climate	1.35	2; 702	0.26
Biomass consumed*fire management	0.06	1; 856	0.80
ΔAveMWT at riparian scale			
Climate	4.13	2; 475	0.02
Fire management	1.14	1; 565	0.29
Climate * fire management	0.27	2; 311	0.77
Biomass consumed	5.59	1; 855	0.02
Biomass consumed*climate	1.93	2; 798	0.15
Biomass consumed*fire management	0.09	1; 786	0.77
Area burned	0.12	1; 940	0.73

climate and fire management scenarios (Fig. 3a). Solar radiation was the next most important factor, contributing 4 % or less to stream temperature changes, with the exception of the B2 climate with suppression which accounted for 12 %, and stream flow had only a minor effect (<1 %). Within fires, air temperature accounted for 71 % of stream temperature change, followed by solar radiation (23 %), with stream flow having a minor effect (6 %; Fig. 3b).

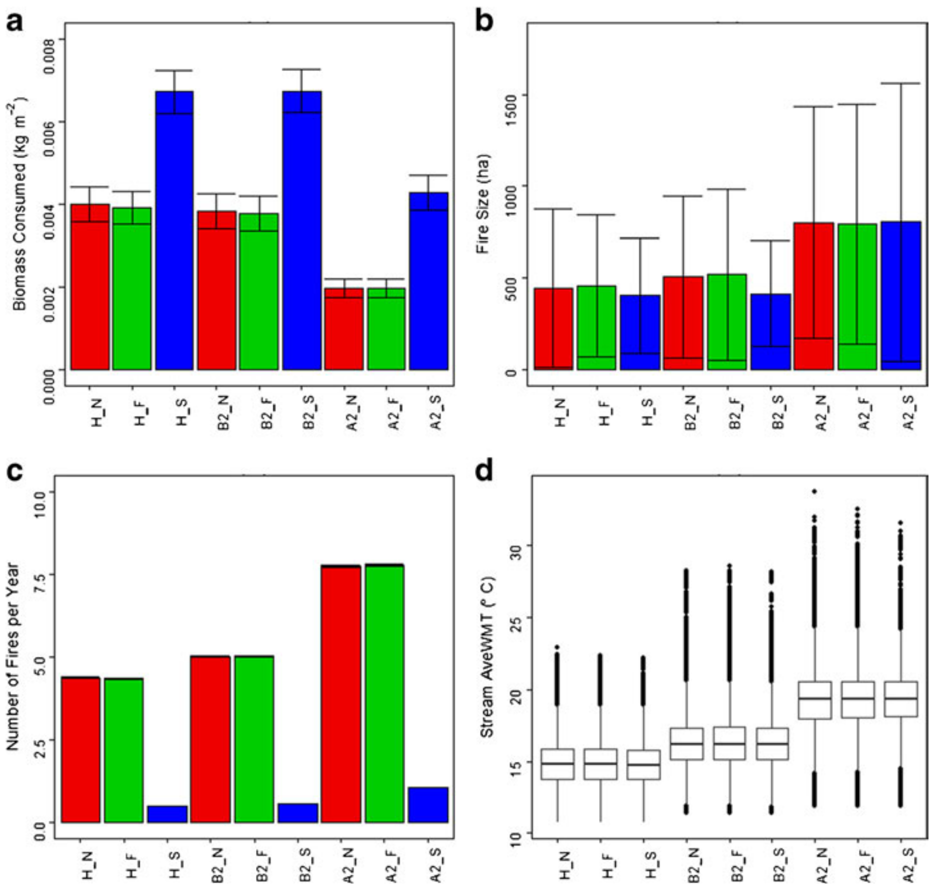


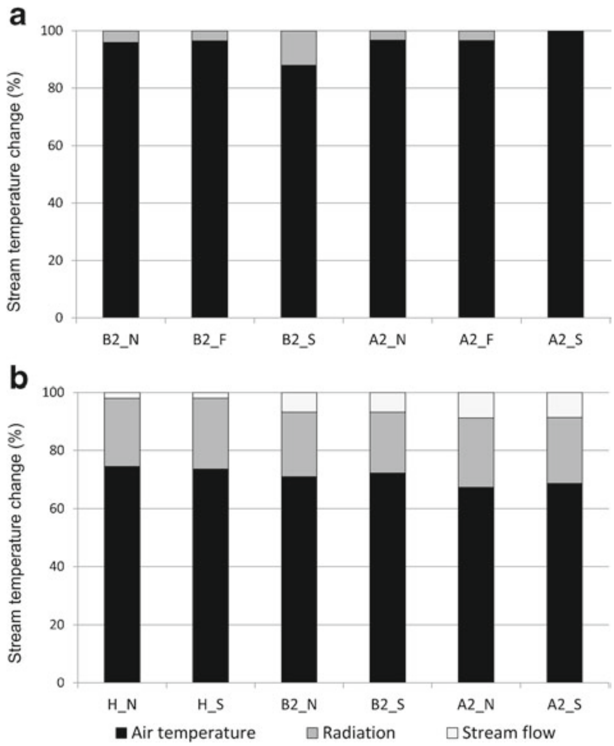
Fig. 2 Mean and standard errors for **a** biomass consumed by fire as a proxy for fire severity, **b** fire size, **c** number of fires per year, and **d** boxplots for average weekly maximum temperature stream (AveWMT) summarized across subwatersheds - for each of the nine climate/fire management scenarios symbolized on the x-axis by combining climate abbreviations (H is historical, B2 and A2) with fire management abbreviations (N is no fire management, F is fuel treatment, S is suppression)

4 Discussion

Our results suggest that future climate conditions will cause major changes to fire regimes in the EFBR but the rise in air temperatures from climate warming will have larger systemic effects on stream temperatures than vegetative changes related to wildfire activity or management measures. Fires increased in size and frequency in our climate change simulations, being most extreme in the A2 (essentially doubling). Fire suppression also clearly altered fire regimes (doubling severity and decreasing frequencies by about 90 %), including concomitant increases to stream-side solar radiation. Yet regardless of scale, these significant changes to wildfire induced only nominal effects to stream temperature compared to the overarching influence of air temperature.

Specifically, at the broadest basin-wide scale, air temperature played the dominant role influencing stream temperatures while solar radiation changes associated with fire was a minor component across all climates. This minimal stream temperature response to fire can in part be

Fig. 3 Percentage of: **a** stream temperature change across the basin from historical conditions to potential future climates (B2, A2) attributable to air temperature, solar radiation and stream flow comparing climate scenarios within three fire management strategies (N is no fire management, F is fuel treatment, S is suppression); **b** stream temperature change within burned areas attributable to air temperature, solar radiation and stream flow across three climate (historical, B2, A2) and two fire management (N, S) strategies



attributed to the scale of assessment in which the total amount of stream network affected by wildfire was relatively small on a mean annual basis. At its maximum impact with the A2 climate, 4 % of the landscape on average burned each year and if a similar subset of the stream network burned annually, then on average a relatively small percentage of streams in the basin would have enhanced solar radiation from fire at any point in time and at a range of levels depending on fire severities. Moreover in the A2 climate, reduced fire severities were indicative of a shift from the historically mixed fire regime to a more frequent, low-severity surface regime which would reduce solar radiation changes along the riparian corridor and dampen stream temperature responses.

At finer scales, climate remained the dominant factor controlling stream temperature but the relative effects of wildfire increased. At the subwatershed scale, the greatest response to fire was in the A2 climate where streams showed a slight trend towards warmer temperatures as high proportions of area burned. That fire effects became apparent at this scale may be because disturbances such as large fires often alter relative stream temperatures in catchments within basins by affecting processes associated with hydrology, sediment budgets, and morphology (Poole and Berman 2001), and from riparian vegetation loss (Johnson and Jones 2000). At the finest spatial and temporal scales in this study, within fires and 1 year post-fire, stream temperature was again mainly influenced by climate with air temperature as the key driver. The role of solar radiation in affecting stream temperature response to fire was small (at most median increases of 0.5 °C, but ranging up to 3 °C) yet more influential than at the basin scale (by about five-fold across climates) emphasizing the greater sensitivity of stream temperatures to wildfire at spatially local and short-term temporal scales.

Although small, our estimates of stream temperature increase associated with wildfire are within range of field-based estimates given the scale of observation. In a study similarly conducted at a basin-wide scale in a nearby central Idaho river, Isaak et al. (2010) found that stream temperatures within fire perimeters increased by 0.65 °C. Larger effects often estimated in other studies may be related to an emphasis on high-severity burns and data collection efforts that oftentimes occurred immediately after fires (1 °C to 6 °C; Dunham et al. 2007; Minshall et al. 1997; Hall and Lombardozzi 2008; Mahlum et al. 2011; Rhoades et al. 2011; Sestrich et al. 2011). Through model simulations, we estimated temperature response to fire over a broad range of temporal and spatial conditions, incorporating variability across 55 weather year types over long time frames (4,000 years) and covering a complex landscape (105,000 ha) with a large spectrum of interacting biophysical factors and ecosystem processes. A substantial range of fire conditions were modeled–with 3,000 to 40,000 fires per scenario, having low to the highest severities–allowing us to fully explore the relative influences of climate and fire on stream temperature across the EFBR landscape.

Since fire disturbance only minimally affected stream temperature response across all spatial scales, it is not surprising that fire management measures also had little effect on in-stream thermal conditions. Fire suppression in our simulations strongly reduced the extent of landscape burned and increased fire severities across all climates, but at broad spatial and temporal scales, the effects on stream temperature were small compared to the influence from climate change. Our fuel reduction treatments (targeting 7 % of the landscape per year) did not alter fire regime characteristics or stream temperature indicating that more intensive treatment, perhaps on the order 20 % or more (Collins et al. 2010) was needed to affect fire regimes. However given that fire only marginally affected stream temperatures and that imposing fire suppression *did* significantly modify fire regimes without noticeable effect on stream temperatures, we suspect that more intensive fuel treatments would at best only minimally affect stream temperatures. We emphasize that our modeling approach implemented both suppression and fuel treatments to effect change at a landscape scale and over long temporal periods. We did not evaluate the benefits from site-specific strategic measures that over short-term periods could facilitate resilient forest and stream habitats and maintain local thermal refuges. Rieman et al. (2010) discuss examples such as focusing treatments at locations sufficiently distant from critical spawning and rearing habitats of cold-water fish species. This type of integrated and careful planning will be especially important for conserving sensitive fish populations as they face particular stressors with climate change (Luce et al. 2012), while at the same time working to minimize the potential for extensive, high-severity fires in landscapes with mixed-severity fire regimes and a recent history of fire exclusion (Collins et al. 2010).

Considerable concern exists for how declining streamflows from predicted hydrologic shifts (e.g. mountain snowpack reduction, earlier snowmelt-derived streamflow timing) will affect stream temperatures (Stewart 2009). Our modeling design simulated most hydrologic changes expected with climate warming, with a 40 % decline in streamflow estimated for the A2 scenario, yet we found only minimal effects from streamflow on stream temperature—consistent with other findings to date that air temperature is a much stronger predictor of stream temperatures than discharge, described in detail by Isaak et al. (2012). Our simulations however assumed the same frequency of extreme weather conditions as the historic record, whereas recent climate projections based on Phase 5 of the Coupled Model Intercomparison Project (CMIP5) global climate model (GCM) predict sharp increases in the frequencies of extremely low spring snow accumulation events in western North America (Diffenbaugh et al. 2013). Future modeling work that integrates CMIP5 GCM ensembles into simulation structures would better predict potential changes to annual hydrographs and the associated stresses on stream temperatures and ecosystems from lower flows.

Modeling necessitates simplification of real-world processes, and several other aspects of our modeling design limited fully capturing biophysical processes that affect stream temperature. For example, for the sake of modeling efficiency, we did not incorporate the downstream accumulation of heat but instead estimated water temperatures independently at each stream cell based on its predictors (i.e., air temperature, stream flow, solar radiation, elevation, channel slope, and contributing area). Including the influence of upstream conditions required characterizing the hydraulic retention time of water through each reach and contact time during which energy exchanges occur (Johnson 2003; Poole and Berman 2001)—a challenging task demanding vastly more simulation time and computer memory. As well, solar radiation estimates used to build the stream temperature regression model contained uncertainty because data were unevenly distributed across their potential range. Future studies could improve solar radiation estimates through the use of high-resolution (e.g., 1×1 m) mapping (Cristea and Burges 2010) or by intensive field measurements at stream temperature monitoring sites. Also, our multiple regression stream temperature model was simplistic in not accounting for spatial autocorrelation among observation sites (Isaak et al. 2014), but it enabled simultaneous assessment of spatial and temporal factors while being computationally efficient for the FireBGCv2 simulations. Ongoing advancements in computing efficiency will resolve many of these issues and could greatly improve subsequent versions of linked landscape dynamics models.

Finally, we had only one downscaled climate change projection (i.e. HadCM3; Mote 2003) available to perform simulations, whereas downscaled output for up to 14 GCMs now exist for our region (Abatzoglou and Brown 2012). In ranked comparisons of GCM performance, Rupp et al. (2013) reported that the HadCM3 GCM was among the high scoring models or intermediate in rank depending on the evaluation method. The HadCM3 GCM had a negative bias (~−2.5 °C) for mean annual temperature not dissimilar from the top ranking model for our region (~−1.5 °C bias; CNRM-CM5) and a positive bias (~15 cm $year^{-1}$) for precipitation somewhat lower than the CNRM-CM5 (~30 cm $year^{-1}$). We expect that had we employed other GCMs such as CNRM-CM5 the differentially strong influence of air temperature would remain comparable given that biases for these models are in the same direction and within reasonable range. Due to the intensive computer demands of FireBGCv2, capacity for simulating multiple GCMs (e.g. at least 10 recommended, Mote et al. 2011) is limited, and capturing uncertainty associated with climate trajectories is challenging, but future FireBGCv2 work would be improved by balancing simulation designs to include a selection of the top performing GCMs.

5 Conclusions

Our dynamic mechanistic modeling approach is the first, to our knowledge, to simulate ecosystem processes with wildfire disturbance across a complex landscape in a spatially explicit context to predict effects on stream temperatures. To summarize, stream temperatures in our modeling processes were governed by three major dynamic variables–air temperature, solar radiation, and stream flow–and each of these variables was directly affected by the interplay of other simulated processes. Air temperature, which had the greatest influence in our stream temperature model, was the least affected by simulated ecosystem process interactions and mostly dictated by input weather, with appropriate adjustments when simulating climate change. Stream-level solar radiation had the next greatest influence and was estimated based on vegetation dynamic processes where changing climatic conditions and fire disturbance influenced forest development. Stream flow had only a minor influence and was predicted mainly from precipitation and topography but also influenced by fire as canopy loss due to burns reduced evapotranspiration rates making more water available to streams potentially decreasing temperatures. Our modeling approach was based on empirical relationships and a mechanistic model developed specifically for the EFBR and application to other watersheds would require refitting. Nonetheless we expect that other snowmelt-dominated Northern Rocky Mountain watersheds with similar vegetation, productivity, and fire regime would demonstrate comparable relative stream responses to climate and fire dynamics under the pyrogeographical framework (Krawchuk et al. 2009) where influences of moisture and weather conditions and resources available to burn vary spatially with predictable patterns such that fire activity across temperate coniferous forests is controlled similarly and mainly as a function of available soil moisture (Krawchuk and Moritz 2011; Moritz et al. 2012).

Exploring future climate changes using this mechanistic-based landscape ecosystem model enabled us to simulate complex ecological interactions and thereby evaluate the potential relative contributions of numerous ecosystem processes, acting across different spatial and temporal scales, to affect stream thermal dynamics. In our process-based modeling, we found that rising air temperature induced increases in stream temperature with a warming climate; however, the minor response in stream temperature to wildfire and fire management strategies was unexpected but depicts a possible outcome when fire effects are considered at broad temporal and spatial scales and across a large range of biophysical conditions. While our modeling approach contained uncertainty in estimating the effect of fire on stream temperature, the relative magnitude of influence between air temperature and fire disturbance on stream temperatures highlights the potential limitations of fire management activities to affect or mitigate the impacts from climate change on stream temperature when considered over long time spans and an extensive expression of fire effects across a landscape. As a result, wildfire suppression and fuels management for mitigating stream temperature increases is most likely to be successful when used to protect small, isolated fish populations that are highly valued. Other solutions for coping with climate change will be needed at broader scales to help fish populations adapt, which should involve formulating broader strategies for restoration and improvement of riparian vegetation. Nonetheless, we stress that when fire management efforts are implemented to reduce fuel continuity and loading especially for near-term benefits, the spatial context should be carefully considered to ensure conservation of high-quality riparian habitat in areas critical to sensitive native fish populations.

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