Climatic Change

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

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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 more 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. Keywords: Stream temperature; landscape modeling; climate change; wildfire; East Fork Bitterroot River, Montana.
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1. Introduction

Aquatic ecosystems are warming due to climate change (Isaak et al. 2012; Schneider and Hook 2010; Webb and Nobilis 2007) and are predicted to continue warming this century (Mantua et al. 2009; Mohseni et al. 2003; Van Vliet et al. 2013). Global circulation models project global mean air temperatures increases from 1.1–6.4°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).

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 Hemisphere 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 United States might be influenced by climate change including direct and indirect effects. 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). 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).

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-hour 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 regression 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 potential 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 fit a global model with all predictors and used stepwise procedures to exclude non-significant predictors to produce the final parsimonious model wherein all predictors were statistically significant at $\alpha < 0.01$. The equation describing the final model included three FireBGCv2 variables and three topographic features, as follows:

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

where T is daily average air temperature (°C), F is stream flow ($m^3 \bullet sec^{-1}$), SR is solar radiation ($watts \bullet m^{-2}$), 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 how flow declines during the summer and affects stream temperature sensitivities. The resulting stream temperature equation accounted for large portions of variability with high predictive ability (daily maximum r_s = 0.84, MAE = 1.70°C, RMSE = 2.21°C), and validation results were reasonably accurate (Online Resource 2). We embedded the stream temperature regression model into 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 simulation experiment.

2.3. *Simulation experiment*

We used a 3x3 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 over the first 100 years of simulations and then held at those levels for 300 years for a total of 400 simulation years. 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 seven-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* ≈ 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 one year before to one 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 temperatures were 5.0°C higher in the A2 climate and 1.7°C higher in the B2 compared to the historical climate (Fig. 2D). 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 became more important at a finer scale. At the basin scale, air temperature accounted for 90% or more of stream thermal changes across all 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).

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 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 were increasingly larger. At the subwatershed scale, the greatest response to fire was in the A2 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 one 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 over emphasis on high-severity burns and data collection efforts that oftentimes occurred opportunistically 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) were 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).

Modeling necessitates simplification of real-world processes, and several 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.

Conclusions

Further research and refinements will increase the ability to predict stream temperature responses to climate change and fire disturbance, but development of this landscape dynamic simulation model approach was an important step. It is the first model, to our knowledge, which simulates ecosystem processes with wildfire disturbance across complex landscapes in a spatially explicit context and correspondingly predicts effects on stream temperatures (Whitlock et al. 2003; Isaak et al. 2010). 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.

Exploring future climate changes using this mechanistic-based landscape ecosystem model enabled us to evaluate the potential relative contributions of numerous ecosystem processes, acting across different spatial and temporal scales, to affect stream thermal dynamics. Spatial ecosystem process models allow the explicit simulation of landscape disturbances (fire) coupled with hydrological flow and vegetation structural responses (Keane et al. 2011). In our process-based modeling, we found that air temperature induced increases in stream temperature with a warming climate; however, the minimal 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 geomorphic, weather, and fire conditions. While our modeling approach contained uncertainty in estimating the influence of fire on stream temperature, the relative magnitude of influence between air temperature and fire disturbance on stream temperatures is reasonable and highlights the potential limitations of fire management tools 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. Managers of aquatic systems may need to find other solutions to tackle climate change impacts on stream temperatures perhaps by focusing on simply adapting to increases or 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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Figure 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).

Figure 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) .

Figure 3. Percentage of: (A) stream temperature change 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.

Fig1
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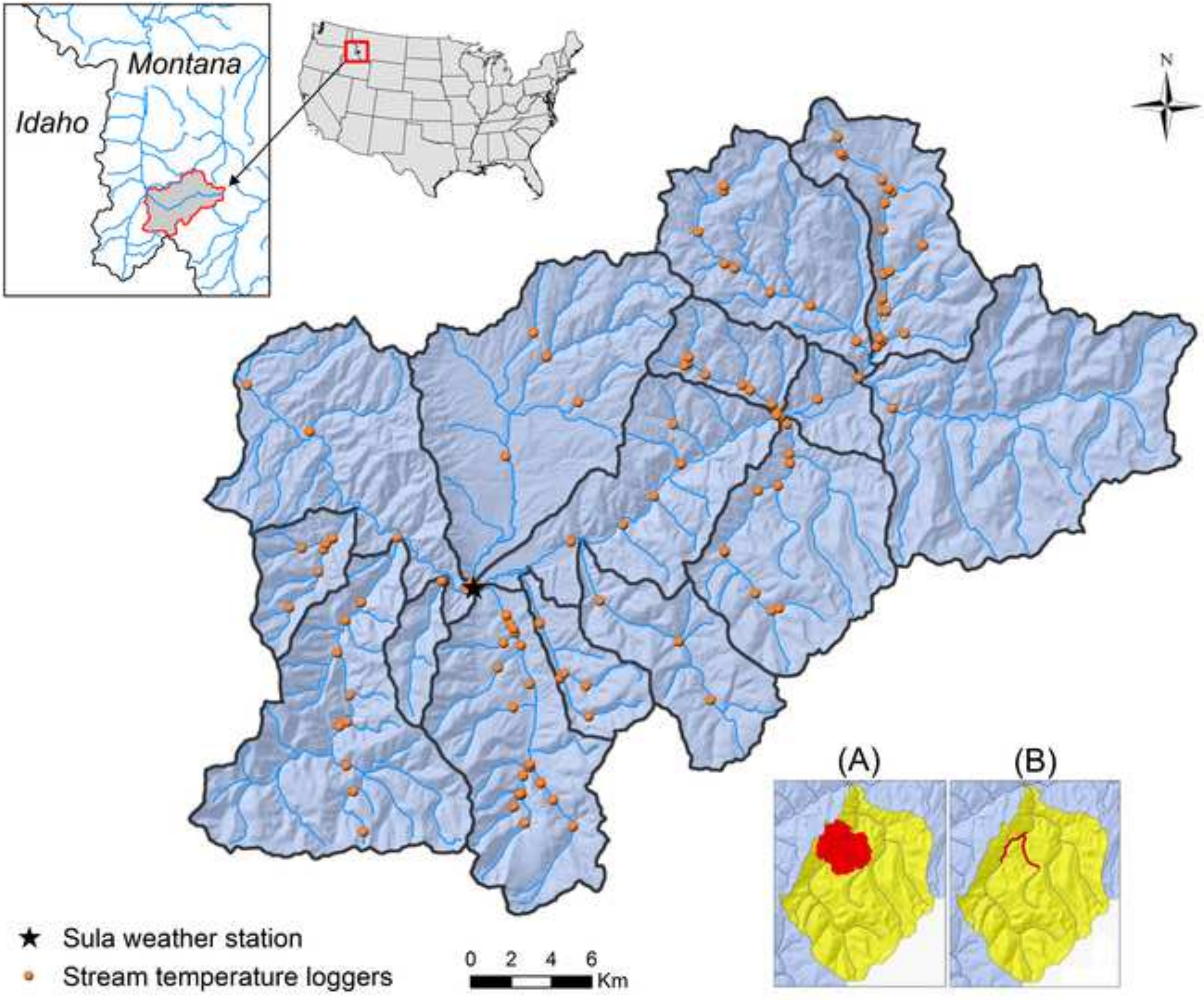

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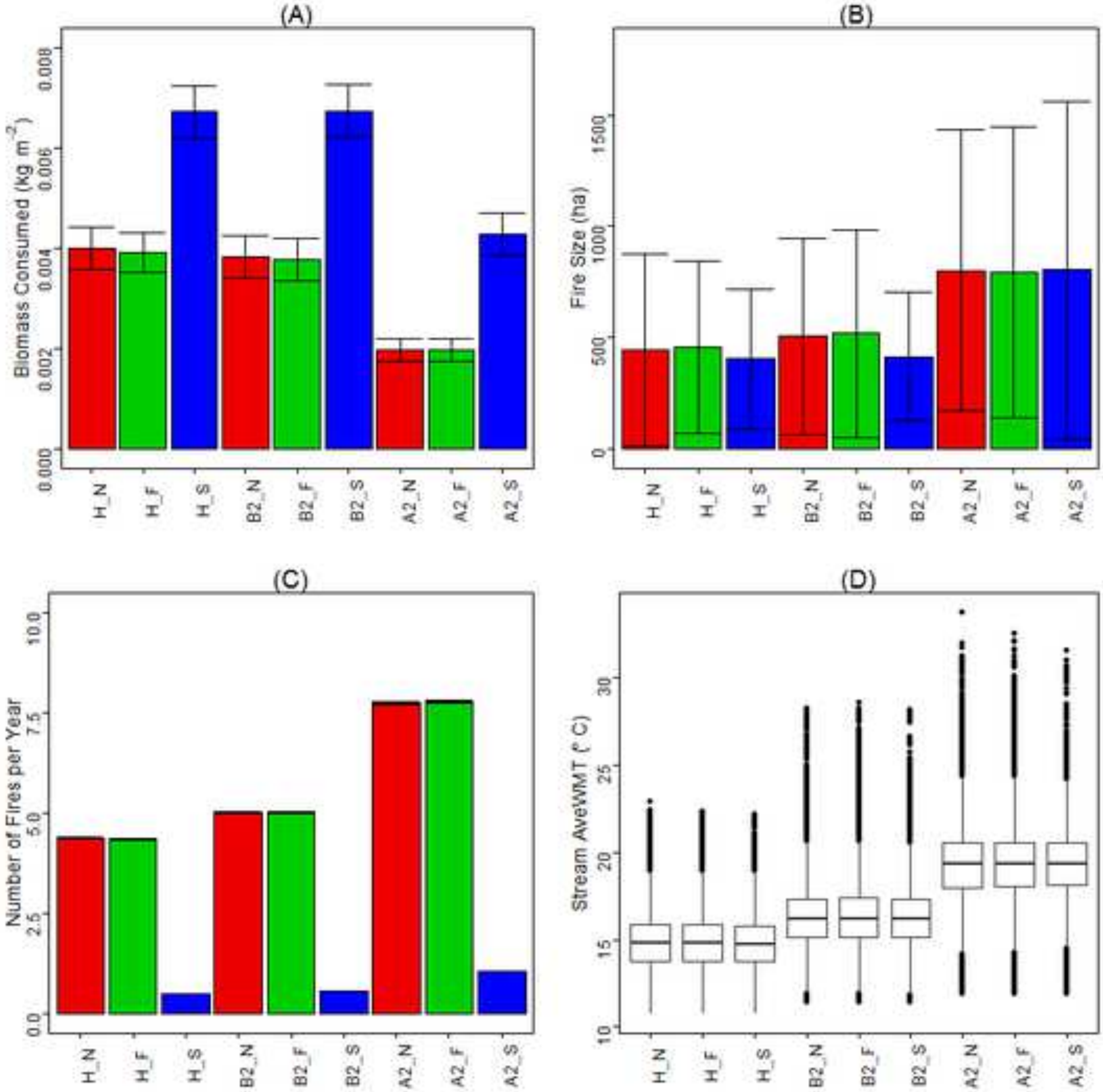

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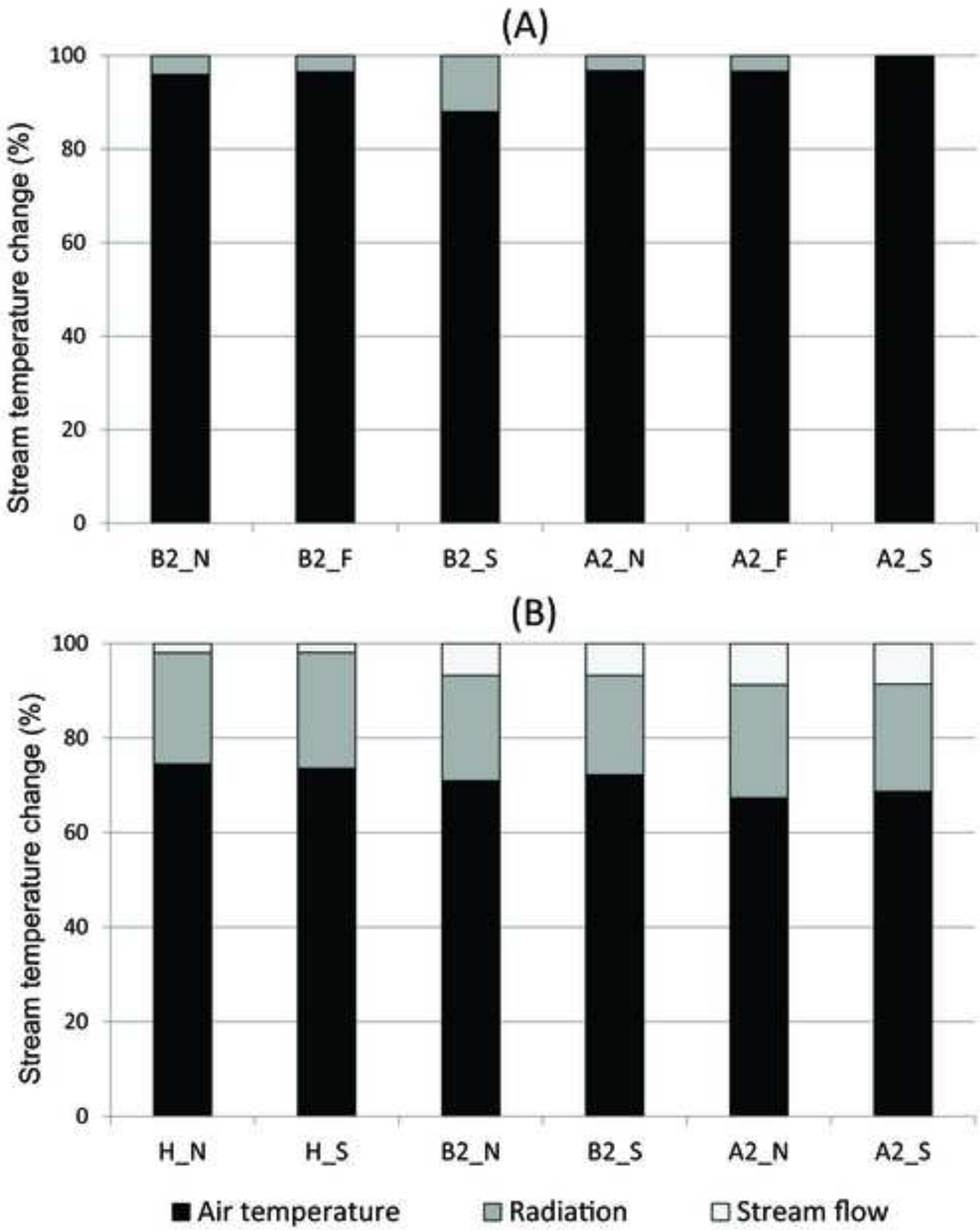

Table 1. Results of generalized linear mixed models for the effects of climate and management on the biomass consumed by fire (kg m^{-2}), fire size (ha), stream AveWMT (average weekly maximum temperature) at the subwatershed scale, change (Δ) in AveWMT in the year prior compared to the year after fire 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	<.0001
Fire Management	134.48	2; 128	<.0001
Climate*Fire Management	3.00	4;128	0.02
Fire Size			
Climate	89.34	2; 188	<.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	<.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

Online Resource 3

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Online Resource 6