JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 55, No. 1 AMERICAN WATER RESOURCES ASSOCIATION February 2019

What Matters Most: Are Future Stream Temperatures More Sensitive to Changing Air Temperatures, Discharge, or Riparian Vegetation?

Steven M. Wondzell, Mousa Diabat, and Roy Haggerty

Research Impact Statement: In the western United States, restoring forests along streams lacking shade can cool streams so much that future stream temperatures could be colder than today, even under a warmer climate.

ABSTRACT: Simulations of stream temperatures showed a wide range of future thermal regimes under a warming climate — from 2.9°C warmer to 7.6°C cooler than current conditions — depending primarily on shade from riparian vegetation. We used the stream temperature model, Heat Source, to analyze a 37-km study segment of the upper Middle Fork John Day River, located in northeast Oregon, USA. We developed alternative future scenarios based on downscaled projections from climate change models and the composition and structure of native riparian forests. We examined 36 scenarios combining future changes in air temperature (ΔT_{air} = 0°C, +2°C, and +4°C), stream discharge (ΔQ = −30%, 0%, and +30%), and riparian vegetation (post-wildfire with 7% shade, current vegetation with 19% shade, a young-open forest with 34% shade, and a mature riparian forest with 79% effective shade). Shade from riparian vegetation had the largest influence on stream temperatures, changing the seven-day average daily maximum temperature (7DADM) from +1°C to −7°C. In comparison, the 7DADM increased by 1.4°C with a 4°C increase in air temperature and by 0.7°C with a 30% change in discharge. Many streams throughout the interior western United States have been altered in ways that have substantially reduced shade. The effect of restoring shade could result in future stream temperatures that are colder than today, even under a warmer climate with substantially lower late-summer streamflow.

(KEYWORDS: climate change; global change; stream temperature; riparian forest; shade; riparian restoration; native salmon and trout; riparian management.)

INTRODUCTION

Populations of salmon, steelhead trout, and char have been listed as threatened or endangered throughout much of their native range (Nehlsen et al. 1991), including the Columbia River Basin (Figure 1a). Many factors have contributed to the decline of these populations, including loss of high-quality freshwater habitat for spawning and rearing (Federal Caucus 2000). Habitat factors are multiple and complex so that no single factor can be identified that accounts for population declines (Gregory and Bisson 1997). However, water quality, especially summer maximum stream temperature is one factor that is clearly implicated in these population declines (Richter and Kolmes 2005; McCullough et al. 2009). Further, high water temperatures have also been identified as a critical barrier to species recovery. Simply put, summer maximum stream temperatures are near lethal or sublethal thresholds (Hicks 2000; Richter and Kolmes 2005) for these species in many streams throughout the interior Columbia River

Paper No. JAWRA-18-0063-P of the *Journal of the American Water Resources Association* (JAWRA). Received April 10, 2018; accepted November 12, 2018. **Discussions are open until six months from issue publication**.

Pacific Northwest Experiment Station (Wondzell), USDA Forest Service, Corvallis, Oregon, USA; and College of Earth, Ocean, and Atmospheric Sciences (Diabat, Haggerty), Oregon State University, Corvallis, Oregon, USA (Correspondence to Wondzell: swondzell@fs.fed.us).

Citation: Wondzell, S.M., M. Diabat, and R. Haggerty. 2019. "What Matters Most: Are Future Stream Temperatures More Sensitive to Changing Air Temperatures, Discharge, or Riparian Vegetation?" *Journal of the American Water Resources Association* 55 (1): 116–132. https://doi.org/10.1111/1752-1688.12707.

Basin and elsewhere throughout much of their native ranges in the conterminous United States (U.S.). There is great interest in restoring salmon and trout populations within their native range. Combined, restoration projects within the Columbia River Basin constitute one of the single most expensive recovery efforts ever undertaken within the U.S., costing many billions of dollars (GAO 2002, Rieman et al. 2015). Climate change, however, raises serious questions about the long-term outcomes of restoration because projected increases in air temperature could make many of these streams and rivers uninhabitable for salmon and trout within a few decades (Battin et al. 2007; Mantua et al. 2010; Isaak et al. 2012).

Climate change projections for midlatitudes consistently agree that air temperatures will warm in the future. However, projecting the influence of air temperature increases onto stream temperature is difficult. Various approaches have been used to predict the magnitude of change in stream temperature that should be expected given projected changes in air temperature. These approaches include developing regional-scale relationships between air temperature and stream temperature (Mohseni and Stefan 1999; Mohseni et al. 1999; Mantua et al. 2010), regional- to local-scale modeling approaches used to relate a variety of landscape, stream network, and channel metrics (e.g., elevation, channel slope, geographic location, etc.) to interannual variation in stream temperatures resulting from coincident variation in climatic drivers among years (Ruesch et al. 2012; Hilderbrand et al. 2014), or even more direct analyses of stream sensitivity to interannual variability in climate (Luce et al. 2014; Garner et al. 2015). However, these approaches are based on past temperature patterns which may not be stationary in time, especially in the face of long-term changes in climate. In fact, stream temperature responses to the observed changes in climate that have occurred to date appear to have been quite complex. Some studies show regional increases in water temperatures that appear related to coincident changes in air temperature (Isaak et al. 2012); other studies have demonstrated that streams, including streams in relatively pristine

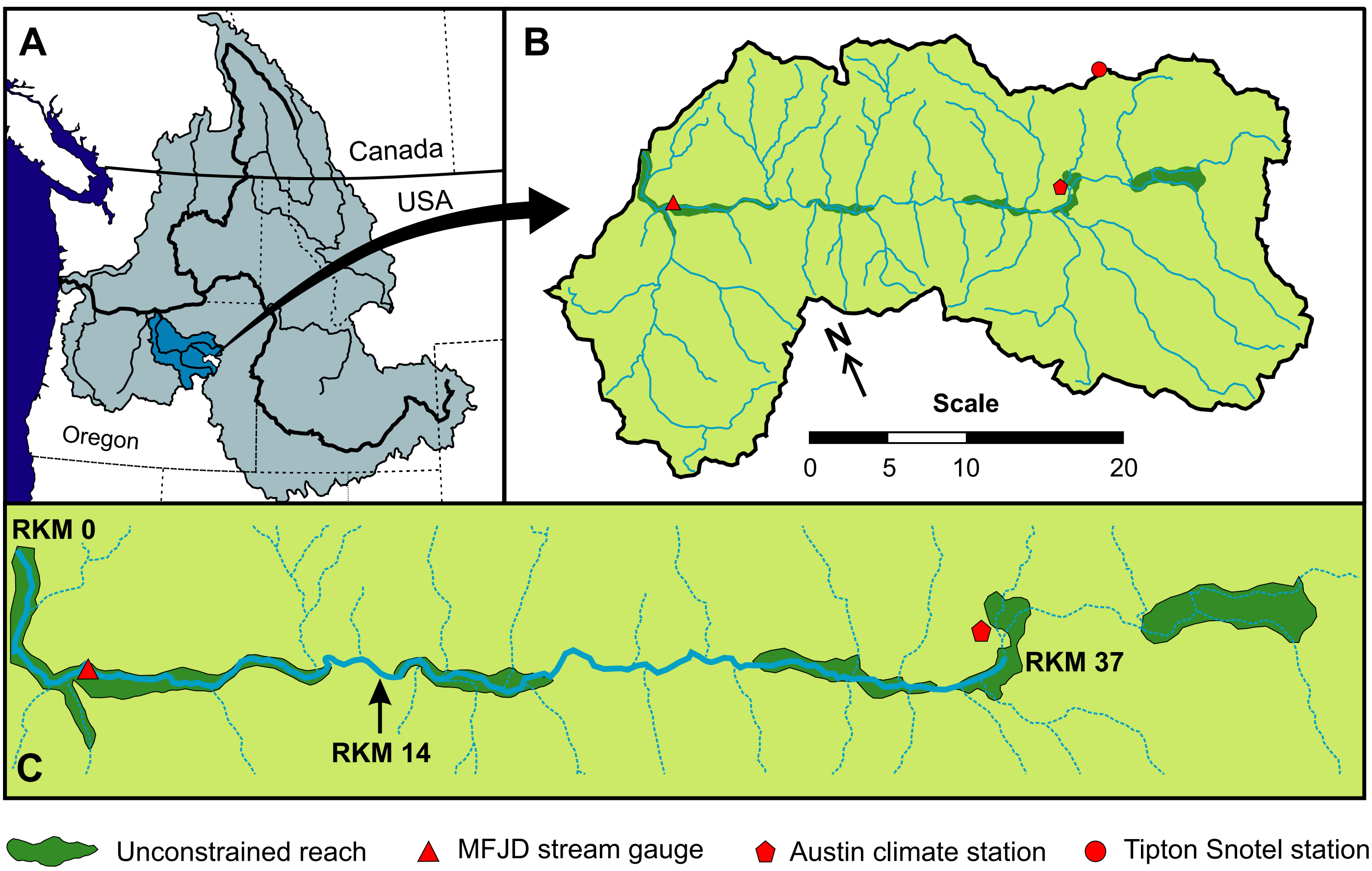

FIGURE 1. Site location map. (a) The location of the upper Middle Fork John Day (MFJD) catchment (white fill) within the John Day catchment (bright blue fill) and its location within the Columbia–Snake River catchments (gray-blue fill) of northwestern USA and southwestern Canada. (b) The upper MFJD with the simulated study segment shown in bold. (c) Close-up of the study segment showing the location of unconstrained valley reaches that have been converted to meadows. RKM, river kilometer.

catchments, have actually cooled over past decades despite well-documented warming of regional air temperatures over the same time period (Arismendi et al. 2012). Further, the regression equations appear to be poor at predicting future temperatures (Arismendi et al. 2014).

Mechanistic stream temperature models provide an alternative to regression-based air-stream temperature relations for predicting stream temperatures under future climatic regimes (Sinokrot et al. 1995). Mechanistic models route water down the channel and attempt to quantify all the heat fluxes into, and out of, the stream, and thus predict the stream temperature. These models are data intensive and usually, only a few of the needed parameters are measured within the stream reach being simulated. Therefore, the model is parameterized using available data, parameter values gleaned from the literature, and climatic data from stations located some distance away. The intensive data requirements and the fact that the models are tuned to fit a limited set of calibration data have led some to question their utility (Luce et al. 2014). However, the calibrated models often do a good job of reproducing observed temperature time series. Consequently, sensitivity analyses of calibrated models may be effective at analyzing the relative importance of different factors on future stream temperatures.

Studies examining stream energy budgets and the relative influence of different energy terms show that shortwave radiation, especially direct-solar radiation, dominates the stream heat budget and is therefore the single biggest determinant of stream temperature on summer days. The result of such studies are empirically confirmed by reach-scale studies of stream temperature responses to forest harvest with and without buffers to provide shade (Moore et al. 2005; Gomi et al. 2006; Janisch et al. 2012) or from experimental shading (Johnson 2004). The results of these studies suggest that changes in shortwave radiation might have larger influence on stream temperature than would changes in air temperature.

Changes in the height or canopy density of forested riparian vegetation shading streams can result in large changes to stream thermal regimes. Thus, the loss of existing shade would amplify the increase in stream temperatures expected from warming air temperatures. Conversely, increasing shade where it is currently limited or lacking could mitigate expected changes in stream temperatures. Wildfire episodically removes riparian forests causing elevated stream temperatures for many years (Dunham et al. 2007) and the extent and severity of wildfire is expected to increase as a result of future changes in the climate (Westerling et al. 2006). Land use and the management decisions that either increase (planting) or decrease (forest harvest) stream shade could also have substantial influence on stream temperatures.

Future climate change may influence stream temperature through indirect effects on stream discharge (Mantua et al. 2010). Ensembles of multi-model and multi-emission scenario simulations tend to project slight decreases in summer precipitation for the Pacific Northwestern U.S. However, these projections are highly variable (Hamlet et al. 2010). These model ensembles also forecast warmer winter air temperatures which would decrease accumulated winter snow packs and lead to earlier snowmelt. Analyses of these climatic forcings with the Variable Infiltration Capacity (Liang et al. 1996) model suggest that climate change will increase the length of summer low flow periods and reduce summer stream discharge. Stream discharge is also directly, and indirectly, influenced by land use. Water is diverted from many small rivers and streams for irrigation and these withdrawals are largest during the growing season — the time when stream discharges are already low, thereby further accentuating the sensitivity of the stream to changes in its energy budget.

These factors — increased air temperature, decreased stream discharge, and loss of stream shade — all have the potential to increase stream temperatures in the future. However, the relative magnitude of the influence of each factor is poorly documented. Further, the potential for riparian restoration to mitigate potential changes is also poorly documented. The objective of this study was to examine potential changes in stream temperature resulting from increased air temperatures and changes in both riparian shade and stream discharge. We identified realistic scenarios for changes in air temperature, shade, and discharge and then conducted a sensitivity analysis using the mechanistic stream temperature model, Heat Source (Boyd 1996; Boyd and Kasper 2003). We examined interactions among these factors to identify potential management decisions that could mitigate expected increases in stream temperatures that are expected to occur over the next 40–80 years.

METHODS

Study Site

The study segment comprises 37 km of the upper Middle Fork John Day River (MFJD) in northeastern Oregon, USA (Figure 1), beginning 1.5 km upstream of the confluence with Clear Creek (44°35′48″N, 118°29′36″W; watershed area is 167 km^2) and ending 3.25 km downstream of Camp Creek (44°42′39″N, 118°48′55″W; watershed area is 827 km^2). Elevation decreases from 1,245 to 1,035 m over this distance, resulting in an average longitudinal gradient of 0.0058 m/m. The valley floor alternates between flatter, unconstrained reaches and slightly steeper moderately to narrowly constrained reaches (Bureau of Reclamation 2008). Precipitation varies with elevation within the watershed, ranging from 625 mm along the watershed divides (Tipton Snotel Site; 1,570 m elevation) to 514 mm along our study segment (station Austin 3 S; Co-Op ID USC00350356; 1,284 m elevation). Annual maximal snow water equivalent of 300 mm occurs from mid-March through early April. Summers are dry with only 8% of the annual precipitation falling in July and August. July and August are the hottest months of the year, with long-term daily maximum air temperatures averaging 28.3°C; December and January are the coldest months with long-term daily minimum air temperatures averaging −10.2°C. Trend analysis from 1981 to 2010 suggests that the monthly average daily maximum temperatures during the summer have increased at 1.1°C/decade ($p < 0.001$; $n = 28$; $r^2 = 0.36$). There is no apparent trend in maximum daily temperatures for other seasons or for mean and minimum daily temperatures or precipitation in any season.

The estimated long-term average discharge at the bottom of our study segment is approximately 4.5 m^3/s, with maximum monthly discharge of 13.5 m^3/s occurring during snowmelt in April or May, and the minimum monthly discharge of 0.6 m^3/s occurring in September. Crown and Butcher (2010) estimated that discharge at the top of the study segment decreased from 0.39 m^3/s in July to 0.15 m^3/s in August 2002. Twenty-one perennial tributaries enter the study segment, and their combined discharge decreased from 0.58 to 0.17 m^3/s over the same period. Thus, tributary inputs account for 50%–60% of the total discharge at the bottom of our study segment. The study segment included four diversions that removed, on average, 0.03 m^3/s from the stream for agricultural use during the summer months. Finally, minor groundwater inflows occur between river kilometer (RKM) 34.55 and 22.00 (Crown and Butcher 2010).

Historic Condition. We examined Government Land Office, land survey records (http://www.glorecords.blm.gov/) to describe the vegetation condition at the time of early Euro-American settlement. The initial land survey was conducted in 1881, and surveyors described the condition of vegetation along each section line (lines marking a uniform square-mile [1.609 × 1.609 km] grid). Ten section lines cross unconstrained valley floors in the upper half of our study segment; the surveyors described the vegetation on seven of these, which we summarize as follows: (1) *Thick growth of willow (Salix* spp.*) and crab apple (likely Crataegus* spp.*) on river bottom*; (2) *Dense thickets of alder (Alnus* spp.*), aspen (Populus* spp.*), and buckbrush (unknown)*; (3) *Heavy timber across much of floodplain*; (4) *Thick growth of willows on river bottom*; (5) *Thick willow brush, river winds, crosses section line three times*; (6) *Graham's field* (fenced and apparently cultivated); and (7) *River bottom nearly level*. While these descriptions are simple, they point out two notable features. First, anthropogenic changes following Euro-American settlement were already well underway by 1881. Second, the descriptions suggest that the riparian corridor was characterized by abundant woody vegetation, often a variety of tall shrubs, but also taller trees. These descriptions contrast starkly with the current vegetation in these same locations, which is mostly open dry meadow.

Land Use and Current Condition. The current condition of riparian vegetation resulted from complex interactions between historical anthropogenic activities, natural disturbance regimes, and plant succession. Unfortunately, early anthropogenic impacts are poorly known, but were likely substantial. Earliest Euro-American impacts resulted from beaver trapping — with beaver effectively extirpated from the John Day River network by the 1860s (Wissmar et al. 1994). Gold mining began about this time, but most mining activity was located on tributaries that enter the MFJD downstream of our study segment. One long, unconstrained reach within our study segment, and the lower ends of two tributaries were dredge mined in the 1930s–1940s. Dredge mining on this mainstem reach only occurred on the northern half of the valley floor, where mineral-rich alluvium was deposited by Granite-Boulder Creek. Within this reach, the river was channelized and coarse rock from dredging spoils was piled onto the floodplain.

The riparian zones of the MFJD have been grazed since at least the 1880s (Wissmar et al. 1994) and grazing of domestic livestock and related activities have led to substantial changes in riparian vegetation. Overall impacts may have been greatest in unconstrained reaches. In most of these, the mainstem was channelized into a single-thread channel, wet meadows were drained, trees and shrubs were cleared, and exotic pasture grasses were planted. Irrigation diversions are also common, with ditches routed along the valley margins such that return flows of water that leaks from the ditches provides "subsurface irrigation" to maintain forage production throughout the dry summer months.

Logging also impacted riparian zones within our study segment. Certainly, logging of the most accessible timber occurred for local uses beginning with Euro-American settlement, but widespread logging was limited by transportation. Logging railroads reached the area in the early 1900s, and were built along the MFJD over the full length of our study segment and temporary tracks were built into several of the larger tributaries. Also, the tributary junction of Clear Creek with the MFJD at the head of our study segment was the site of a company mill town and logging mill that operated from 1917 to 1975. Early logging practices would have substantially influenced riparian vegetation because the railroad followed the valley floors and trees growing in the riparian zone and lower hillslopes would have been easily accessible (Beschta 2000). Logging volumes peaked from the 1950s through the early 1980s (Wissmar et al. 1994) and have been declining since then, in part from the development of state forest practice rules and federal land management rules that dramatically changed logging practices in recent decades. Logging in riparian zones on federal lands is no longer occurring.

Residual riparian forests remain within our study segment. Confined reaches tend to be the most heavily forested, and are dominated by native conifers, including ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*). Native hardwoods are much less abundant. Black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) is present throughout the study segment but it usually occurs as widely scattered, individual large trees. A few denser stands of cottonwood are present. Regeneration of cottonwood does not appear to be occurring as seedlings, saplings, and small trees are lacking (Beschta and Ripple 2005). A variety of riparian shrubs are also present. Mountain alder (*Alnus incana*) is relatively common, and found on streambanks in many locations. Both black hawthorn (*Crataegus douglasii*) and large willows (*Salix* spp.) are present in some locations, although these are typically heavily browsed.

Heat Source Simulations

Stream temperature was simulated using the mechanistic model, Heat Source v. 8.04 (Boyd 1996; Boyd and Kasper 2003). This numerical model tracks the net heat flux (H_{net}) into or out of a stream reach as water flows down a stream channel, the components of which are:

$$H_{\mathrm{net}} = H_{\mathrm{shortwave}} + H_{\mathrm{longwave}} + H_{\mathrm{convection}} + H_{\mathrm{latent}} + H_{\mathrm{conduction}},$$

where $H_{\mathrm{shortwave}}$ is the heat flux from solar radiation received at the surface of the stream; H_{longwave} is the net heat flux at the surface of the stream resulting from incoming and outgoing longwave radiation; $H_{\mathrm{convection}}$ is the net heat flux directly to, or from, the atmosphere at the surface of the stream; H_{latent} is the net heat flux caused by evaporation of water vapor from the stream surface or condensation of water vapor onto the stream surface; and $H_{\mathrm{conduction}}$ is the net heat flux across the streambed caused by differences in water and substrate temperatures. The model also accounts for advective heat fluxes from inflows of water from tributaries, groundwater, and hyporheic exchange. The full solution of the heat budget equation and its application to streams in the Heat Source model is described in detail by Boyd and Kasper (2003).

A version of the Heat Source model had been parameterized and calibrated by Crown and Butcher (2010) to simulate stream temperatures of the MFJD for 2002 and used for Oregon Department of Environmental Quality's Total Maximum Daily Load (TMDL) (ODEQ 2010) analysis of stream temperatures in the John Day River Basin. We used this version of Heat Source for our base-case simulations. Thus, 2002 became the base case against which future stream temperatures were compared.

We made minor modifications to the model that ODEQ had previously calibrated to the upper MFJD, including extracting and running independently just the uppermost 37 km of the model, reducing the size of the finite-difference elements from 300 to 100 m, and embedding our version of Heat Source in a user interface to facilitate model inputs when making multiple model runs and to facilitate analysis of simulated stream temperatures and heat budget terms.

Boundary Conditions. Simulating the effects of future climate on the thermal regimes of the upper MFJD was complicated by difficulties in setting realistic boundary conditions for the model. Our study segment did not start at the headwaters of the stream, thus we must specify an hourly time series of stream temperature at the upstream boundary. But stream temperature is highly influenced by shade, which in turn can be influenced by land use decisions. Because there are many large open meadow reaches upstream of our study segment, the base-case water temperatures in 2002 were warm. We chose to use the 2002 base-case temperatures for the upstream boundary and both the tributary and groundwater inflows. The effect of the upstream boundary conditions were explored in a sensitivity analysis in which the model was run iteratively, taking the output stream temperature time series at the bottom of the study segment from the first model run and using it as the upstream boundary condition for the second model run and so on, for five iterations. This analysis showed that the 37-km long study segment was sufficiently long that the temperature at the downstream sites used to evaluate our future scenarios was close to the equilibrium temperature expected for the reach under those scenarios. Thus, our choice of upstream boundary condition had little influence on the results reported here.

We also examined the influence of lateral boundary condition temperature for tributary and groundwater inflows to the study segment. We increased the temperatures of both the tributary and groundwater boundary time series by a uniform 1°C and compared differences in projected stream temperatures among the simulations. These analyses showed that the model simulations were sensitive to the temperature of lateral inputs. In fact, a 1°C increase in the lateral boundary temperature time series led to an approximate 2°C increase in the downstream seven-day average daily maximum temperature (7DADM). It is important to note, however, that there are a number of relatively large tributary and groundwater inputs within the lower portion of our study segment. These inputs are not in the channel for sufficiently long for the temperature of the mainstream to reach equilibrium.

Future Climate and Riparian Vegetation Scenarios. We used Heat Source to simulate both base-year 2002 and future stream temperatures. To do this, we needed to identify reasonable future scenarios for model inputs under a changed climate. The Climate Impact Group (CIG) at the University of Washington has downscaled future climate projections from the Fourth Intergovernmental Panel on Climate Change (IPCC 2007), for a large number of stream gauging sites throughout the interior Columbia Basin (Hamlet et al. 2010, 2013). The Variable Infiltration Capacity model was then run using the downscaled climate to project hydrologic changes at each gauging site (Hamlet et al. 2010, 2013). Monthly averages of both the downscaled climate and the hydrologic projections for 2020s, 2040s, and 2080s, based on ensembles of 10 Global Climate Models (GCMs), for both the A1B and B1 emission scenarios, are available from the web (http://warm.atmos.washington.edu/2860/).

Hamlet et al. (2010, 2013) did not include the MFJD River Basin in their climate projections. Therefore, we derived changes in projected air temperatures by averaging projections for 10 gauging stations close to the MFJD, all within the Blue Mountains of northeast Oregon (see Diabat 2014, appendix A for more details). All gauging stations showed increases in summer air temperatures, with an average increase 1.8°C in the 2020s, 2.8°C in the 2040s, and 4.5°C in the 2080s. We chose to model air temperature increases of 2°C and 4°C as reasonable scenarios of air temperature increases for this region over the next many decades. We did so using the delta method (Gleick 1986; Hay et al. 2000; Diabat et al. 2012), adding the change in temperature to the 2002 base-case time series of hourly air temperatures. We did not have a way to project concurrent changes in relative humidity and wind, so we did not change these input data files.

We also derived future stream discharges from the 10 stream gauges analyzed by CIG, as described above. The model ensemble projected that July–August discharge would decrease by −1.9% in 2020 and by −5.8% in 2080. However, projections from individual models ranged from −31% to +37% in 2020 and from −49% to +57% in the 2080s. We were concerned that very small changes in discharge projected from the ensemble average would not lead to detectable changes in stream temperature, and given the high variability in projected changes, we chose to explore scenarios with uniform ±30% changes in discharge, applying these changes to discharge at both the upstream boundary and to each tributary entering our study segment. Note that the impacts of extreme events could be considerably larger than the conditions we simulated. There are only two years of discharge records available near the bottom of our study reach, but historical records (1929–2013) from the gauge at Ritter, Oregon (located some 52 km downstream) shows that the range in monthly July and August stream discharge varied from −78% to +238% of the long-term mean.

We did not modify diversions from the stream nor did we modify the groundwater inputs used by Crown and Butcher (2010). Irrigation diversions over the summer averaged 0.03 m^3/s, and are small relative to the expected long-term average July and August discharge of 1.04 m^3/s, and even small relative to the lowest expected discharge of 0.46 m^3/s (expected discharges are adjusted to long-term records at the Ritter gauge based on the ratio of discharges in the two years of common record, 2012 and 2013). Because we did not modify the irrigation diversions nor the groundwater inputs, the discharge at the bottom of the study segment over the simulation period ranged from 120% to 125% of the 2002 base-case discharge in our high discharge scenario and from 75% to 80% of the base-case discharge in our low discharge scenario.

Riparian vegetation was modified to represent three potential scenarios in addition to base-year 2002 conditions. Crown and Butcher (2010) used a combination of aerial-photographic interpretation and field surveys to map the structure and composition of the riparian vegetation in 2002, from which Heat Source calculated effective shade. The effective shade (the ratio of the received shortwave radiation to the potential shortwave radiation) for the base case averaged 19% and ranged along the study segment from nearly 0% to as much as 90% in a few locations (Figure 2). We generated homogeneous riparian vegetation layers for our alternative scenarios as follows: a post-wildfire scenario in which canopy height averaged 1 m and canopy density averaged 10% and resulted in 7% average effective shade (mostly as topographic shade); a young, open forest scenario where regenerating trees had grown to 10 m height and 30% canopy density providing 34% effective shade; a mature riparian forest scenario with trees 30 m tall and 50% canopy density with 79% effective shade (Figure 2).

The tree heights used in our scenarios are reasonable in light of the potential height of native riparian species in the upper MFJD. A query of the U.S. Forest Service's Forest Inventory and Analysis (FIA) data (Donnegan et al. 2008) for the heights of trees growing within 30 m of a perennial water source in eastern Oregon showed that the 90th percentile heights of dominant conifers such as ponderosa pine, grand fir, and Douglas fir exceeded 40 m. Similarly, we found an average height of 30.4 m ($n = 62$) for conifers measured in 13 randomly located riparian plots within the upper MFJD. Cottonwoods were uncommon. Only four were recorded in the FIA dataset; only seven were present in the upper MFJD plot data. However, heights of tall cottonwoods ranged from 20 to 32 m.

Simulating all possible combinations of the different scenarios for air temperature (base case or +0°C, +2°C, and +4°C), stream discharge (−30%, base case or ±0%, +30%), and riparian vegetation (2002 current condition, post-wildfire, young forest, mature forest) resulted in 36 simulations.

Temperature and Heat Budget Analyses. Our study specifically focused on late-summer warm temperatures because the upper MFJD and many of its tributaries are listed as Water Quality Limited for temperature with U.S. Environmental Protection Agency-approved TMDLs and Water Quality Management Plans (ODEQ 2010). Further, die-offs of adult salmon occurred within our study segment in both 2007 and 2013 due to high water temperatures, and in 2013 resulted in an estimated loss of 60% of the adult spawning population (Jim Ruzycki, Oregon Department of Fish and Wildlife, unpublished data, 2013). There are many potential metrics we could have used for analysis (see for example Arismendi et al. 2013). We chose the seven-day running average of daily maximum stream temperature because it is a regulatory criterion for water quality in the State of Oregon. Therefore, we compared our simulations using the 7DADM, which we calculated for each 100-m long finite-difference element along the 37-km long study segment for each model run. Thermal requirements of cold water-dependent fishes vary with species and life-history stage. For spring Chinook salmon in the MFJD, only rearing juveniles and adults are present in late summer. Optimal temperatures for rearing range from 10°C to 15.6°C (McCullough et al. 2001) with an optimal 7DADM < 16.5°C (Hicks 2000). Lethal temperatures vary, but high mortality occurs when daily maximum temperatures exceeded 22°C (Hicks 2000; Richter and Kolmes 2005). Correspondingly, the State of Oregon's numeric criteria are a 7DADM < 16°C for core cold water habitat and <18°C for salmon and trout rearing (ODEQ 2008).

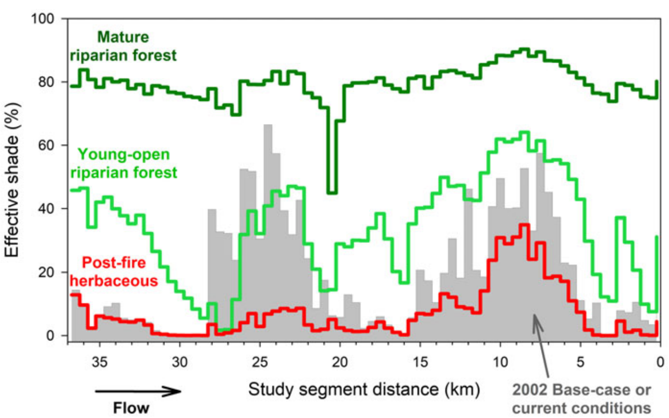

FIGURE 2. Effective shade on July 14 over the length of the study segment for four riparian vegetation scenarios.

We examined the heat budget for each scenario at RKM14. There are only a few relatively small tributaries entering the mainstem MFJD for many kilometers upstream of this site. Also, this location is sufficiently distant from the upstream boundary of our study segment that stream temperatures and the stream's heat budget was not heavily influenced by our choice of boundary conditions. This site is also located within an open meadow (RKM16 to RKM21) where effective shade averages 19% under the base-case conditions so that changes in the energy budget will reasonably reflect changes in effective shade occurring over the length of the study segment.

Our response metric, the 7DADM, is averaged over seven days, therefore we also analyzed the heat budget over the corresponding seven-day period. The date of the 7DADM, however, ranged from July 14 to 17 at RKM14 among the 36 scenarios we examined. In order to make consistent comparisons of the heat budgets among these model scenarios, we chose to analyze the seven-day period July 8–14, because the base-case 7DADM occurred on July 14.

We present heat exchange per unit length of stream channel, which we call the heat flow (W/m), which is the heat flux (W/m^2) multiplied by the channel's width at the water surface (m). Representing terms in the energy balance as heat flow enables direct comparisons of heat exchange at locations and times for which width differs. Heat flow can be interpreted as energy change in a unit of water per unit distance travelled.

RESULTS

Changes in Stream Temperature

Shade was the single biggest factor influencing the projected 7DADM along our 37-km-long study segment, regardless of changes in air temperature or stream discharge (Figures 3 and 4). At the very bottom of the study segment (RKM0), we observed a 10°C range in 7DADM from changing just riparian vegetation (Figure 4), whereas changes in air temperature and stream discharge led to an ~2°C range in the simulated 7DADM. These patterns were similar at RKM14, where we observed an 8°C range in 7DADM from changing just riparian vegetation, whereas changes in air temperature alone resulted in 1.4°C range in 7DADM and changes in stream discharge alone resulted in a 0.7°C range in the simulated 7DADM (Figure 4).

Changes in shade, air temperature, and stream discharge influenced the thermal regime in different ways (Figure 3a–3c). For example, an analysis of hourly stream temperatures for the seven-day period over which the stream reached its 7DADM at RKM14 showed that increasing effective shade from the base-case to the mature forest scenario decreased daily maximum stream temperatures by 7.8°C, decreased the daily average stream temperatures by 4.5°C, but only decreased the daily minimum stream temperatures by 1.6°C (Figure 3a). The influence of increased air temperatures was relatively uniform over the entire 24-hour daily cycle in stream temperatures such that the 4°C increase in air temperature increased the minimum, average, and maximum daily temperatures by 1.4°C (Figure 3b). Finally, the influence of changing discharge was quite different. Increasing the discharge from −30% to +30% reduced the daily maximum stream temperatures by 0.7°C but *increased* the nightly minimum stream temperatures by 1.3°C. Changing discharge did not influence the daily average stream temperature (Figure 3c).

The simulations showed that loss of shade from a large-scale disturbance such as a wildfire burning the entire study segment would increase the 7DADM relative to the base case (Figure 3a). The increases are relatively modest because much of the upper MFJD currently flows through wide, open meadows where there is little shade (Figures 1 and 2). Thus, the change from the base case to the post-wildfire vegetation (1 m tall; 10% canopy density) only reduces the average effective shade from 19% to 7%. The resulting changes in 7DADM are smallest for the scenario with +30% increase in stream discharge and no change in future air temperature; however, a 4°C increase in air temperature and a −30% decline in stream discharge, coupled with the loss of existing shade increased the 7DADM over most of our study segment by 3°C–5°C (Figure 4).

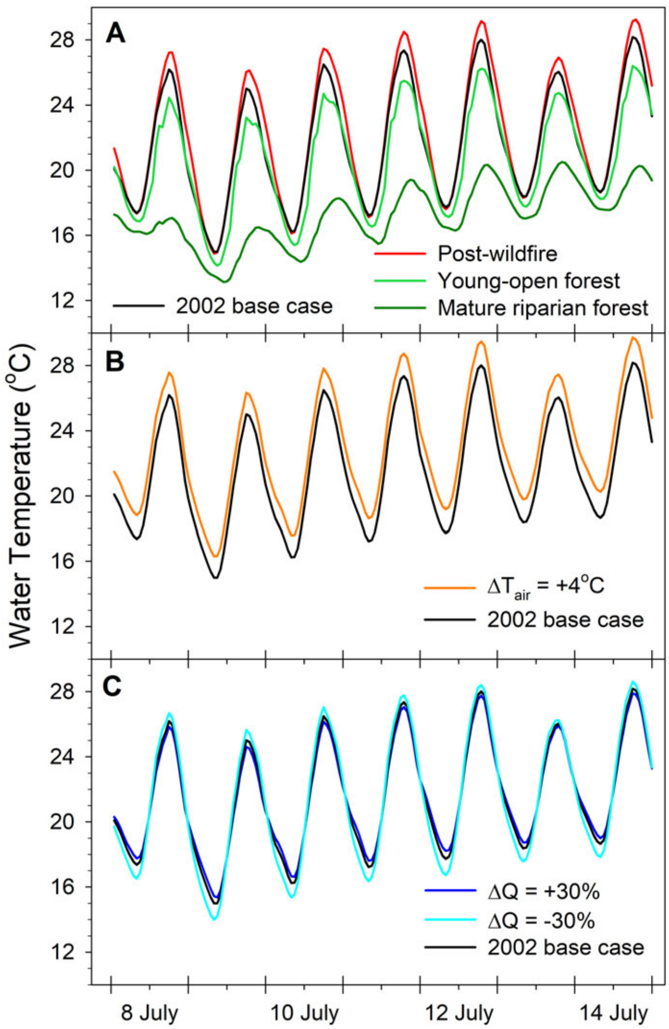

FIGURE 3. Hourly stream temperature time series at RKM 14.05 for the seven-day period over which the heat budget is summarized (see Figures 5 and 6). (a) Four riparian vegetation scenarios with 2002 base-case conditions for air temperature (T_{air}) and discharge (Q). (b) Two air temperature scenarios with 2002 base-case conditions for riparian vegetation and Q. (c) Three discharge scenarios with 2002 base-case conditions for riparian vegetation and T_{air}.

The simulations showed modest change in 7DADM under the young-open forest vegetation scenario relative to the base case (Figure 3a). The results, however, varied with location along the study segment, with the 7DADM actually warmer than the 2002 base case from RKM27 to RKM18. However, the 2002 base-case effective shade is high from RKM30 to RKM24 so that the young forest scenario actually leads to a decrease in effective shade over this portion of the study segment (Figure 2). From RKM20 to RKM5, the young-open forest scenario increases effective shade by 22%, so that the 7DADM decreases relative to the base-case scenario. There is substantially less effective shade in the lowest 5 km of the study segment so that the 7DADM increases rapidly over these 5 km (Figures 2 and 3a). Finally, the 7DADM is also sensitive to underlying changes in stream discharge and air temperature over the entire study segment (Figure 3b, 3c). If air temperatures do not increase, 7DADMs will be lower than the base-case scenario under increased discharge, whereas under decreased discharge and increased air temperatures, the 7DADM is higher than the base case (Figure 4).

The scenarios with mature riparian forest, characterized by 30-m tall trees with 50% canopy density, showed large decreases in 7DADM over the entire 37-km study segment (Figure 3a). These decreases ranged from 5.8°C to 7.6°C at RKM14 and from 7.1°C to 8.9°C at RKM0 (Figure 4). Surprisingly, the 7DADM was warmer under the mature forest scenario at high discharge (+30%) than at low discharge (−30%). The decrease in the 7DADM was persistent over all scenarios examined, even in the face of a 4°C increase in air temperature (Figure 4).

Heat Budget Analysis

The heat budget was analyzed for the 100-m reach located at RKM14 where effective shade across the

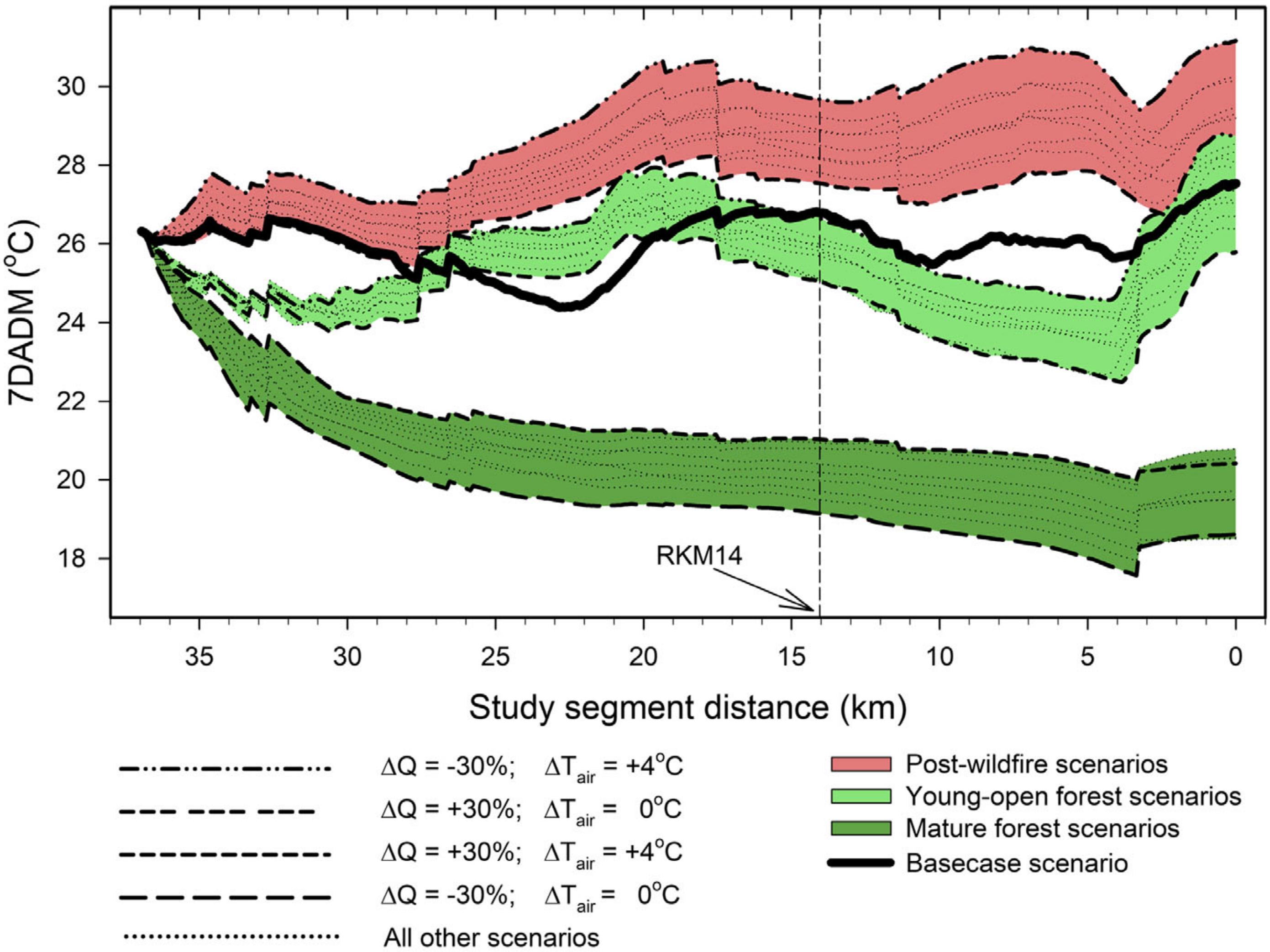

FIGURE 4. Simulated seven-day average daily maximum temperature (7DADM) stream temperatures over the length of the study segment. Simulation results are grouped for three riparian vegetation scenarios (shaded zones) bounded by bold lines representing combinations of T_{air} and Q representing the scenario with the warmest or coldest simulated 7DADM stream temperatures. Note that under both the post-wildfire and young-open forest scenarios, the +30% Q simulations result in the coldest stream temperatures. This pattern is reversed under the mature forest scenario where the +30% Q simulation results in the warmest stream temperatures.

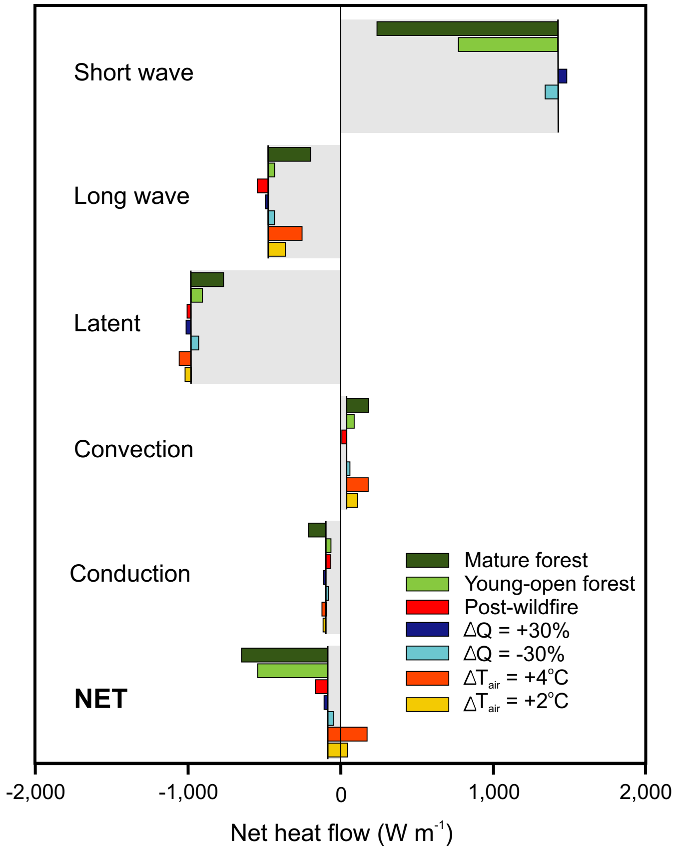

FIGURE 5. Differences in the net heat flow for each term in the heat budget for the 100-m analysis reach at RKM13.95, relative to the 2002 base-case scenario, calculated over the seven-day period (July 8–14) during which the 2002 base-case scenario reached its 7DADM stream temperature (July 14). The net heat flows for the 2002 base-case scenario are shown as wide horizontal bars that are shaded light gray and bounded by thin, vertical black lines. Differences between the 2002 base-case and other model scenarios are shown as horizontal bars "based" on the thin vertical lines from the 2002 base case. Horizontal bars extending to the left of the vertical line indicate that the stream lost heat relative to the 2002 base case; horizontal bars extended to the right indicate that the stream gained heat relative to the 2002 base case. The right or left end points of each horizontal bar indicate the actual net heat flow for each scenario. Scenarios shown here are limited to those in which only a single factor was changed (riparian vegetation, T_{air}, or Q).

vegetation scenarios was similar to the entire 37-km study segment: base case RKM14 = 19% vs. 19% for the study segment; post-wildfire RKM14 = 12% vs. 7% for the study segment; open-young forest, RKM14 = 52% vs. 43% for the study segment; mature forest RKM14 = 85% vs. 79% for the study segment. Effective shade had a much larger influence on the heat budget in this reach than did changes in either air temperature or discharge (Figure 5). Effective shade under the mature forest scenario reduced heat gains from shortwave radiation by more than 80% relative to the base-case scenario, and because shortwave radiation was the largest single term in the heat budget, large changes in effective shade caused large changes in stream temperature. Heat Source simulated a 48% decrease in heat gained from shortwave radiation under the young-open forest scenario (Figure 5). Finally, because the difference in shade between the base-case and the post-wildfire scenarios was small, there was little difference in shortwave component of the heat budget for these two scenarios.

The 100-m heat budget reach dissipated heat via the net exchange of longwave radiation, although the magnitude of this exchange was heavily influenced by vegetative cover and air temperature (Figure 5). Specifically, both increased air temperature and increased height and density of the riparian forest canopy decreased the amount of heat dissipated by the stream via net longwave radiation. Restoration treatments that grow tall, dense-canopied riparian vegetation would limit the stream's exposure to the sky, so that more longwave radiation is exchanged with much warmer riparian vegetation. At the same time, the more heavily shaded stream is cooler and thus emits less outgoing longwave radiation. The net result is that increases in canopy cover reduce the streams loss of heat via longwave radiation. These effects were proportional to the change in the riparian canopy, with the young forest scenario only slightly reducing the net dissipation of heat via outgoing longwave radiation, whereas the more open post-wildfire scenario actually increased the amount of heat dissipated.

The stream also dissipated less heat via outgoing longwave radiation in scenarios with warmer air temperatures. Water temperatures also increase under this scenario so the stream would emit more outgoing longwave radiation. However, in the simulations where air temperature increased without changing the riparian vegetation, the amount of downwelling longwave radiation also increased. These increases in downwelling longwave from the atmosphere were larger than the increase in the stream's outgoing longwave, so the net result is to reduce the amount of heat the stream dissipates via longwave radiation (Figure 5). The influence of increased air temperature combined with a mature riparian forest canopy was so strong that net longwave heat exchange becomes positive. That is, the stream has a net gain in heat from longwave radiation (Figure 6).

Changes in stream discharge also influenced the radiant heat flux from both shortwave and longwave radiation; however, these effects were small relative to the influence of shade and changing air temperature (Figure 5). Discharge is related to the wetted width of the channel and thus the potential area of the stream surface over which radiant fluxes occur. The stream was gaining heat via shortwave radiation so that increasing discharge increased shortwave heat inputs and decreasing discharge decreased these inputs. Conversely, the stream was losing heat via

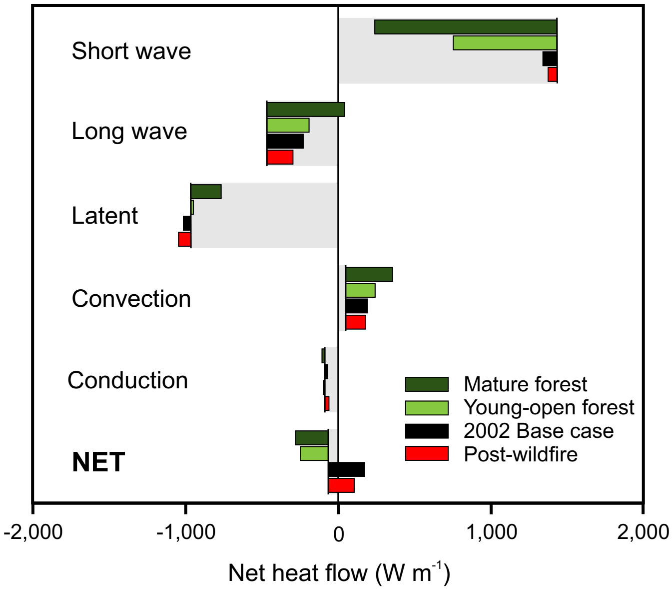

FIGURE 6. Differences in the net heat flows for each term in the heat budget for the 100-m analysis reach at RKM13.95. The four scenarios shown here illustrate the effect of changing riparian vegetation under the most likely future scenario in which ΔT_{air} = +4°C and ΔQ = −30%. See caption of Figure 5 for details.

longwave radiation so that decreasing stream discharge decreased the heat dissipated via longwave radiation, whereas increasing discharge increased the amount of heat dissipated.

Evaporative cooling (latent heat) substantially influenced the heat budget of the 100-m reach that we analyzed. Because we held relative humidity and wind speed constant in all scenarios, the magnitude of evaporative cooling was a direct function of stream temperature, where the warmest water drives the highest rate of evaporation (Figure 5). The differences among scenarios are greatest during the day, when the differences in stream temperatures among the vegetation scenarios are largest, and much smaller at night. Summing the heat exchange over both night and day shows that the differences among the scenarios are such that the net effect of evaporation is to reduce the dissipation of heat in the mature forest scenario and slightly increase the dissipation of heat in the post-wildfire relative to the base-case vegetation scenario (Figure 5).

Convection and conduction were the smallest heat exchange terms in our simulations (Figures 5 and 6). Conduction changed very little among scenarios, whereas convection generally led to increased heat gains by the stream, relative to the base case. Because wind speed was held constant, differences in convective heat gains among scenarios became a direct function of the temperature gradient between the stream and the air. Stream temperatures were much cooler in heavily shaded scenarios which also resulted in a larger heat gradient between the air and the water, leading to greater convective transfer of heat to the water.

The net effect of all the heat budget terms, combined, showed that the 100-m analysis reach was slightly losing heat under base-case conditions (Figures 5 and 6). Increasing air temperature or decreasing stream discharge tended to shift the net heat exchange in the positive direction (gaining heat), but that this effect was small for changes in discharge. Conversely, increasing the effective shade or increasing discharge tended to shift the net heat exchange in the negative direction (losing heat). Under a future climate when air temperatures are 4°C warmer and discharge is 30% lower, in both the post-wildfire and base-case vegetation scenarios, the small reductions in shortwave inputs from reduced wetted width are more than offset by increasing heat inputs from convection and net increases in longwave inputs so that the 100-m reach gains heat relative to the base-case scenario (Figure 6). Conversely, for the young-open and mature riparian vegetation scenarios, the reductions in shortwave radiation from stream shading are larger than the changes in heat fluxes from evaporation, longwave radiation, and convection so that the 100-m reach loses heat relative to the base-case scenario (Figure 6).

Interactions between Shade, Discharge, and Air Temperature

The influence of stream discharge on the 7DADM varied among scenarios and with location along the study segment (Figure 7a). If the stream's net energy budget was positive (gaining heat), the 7DADM was higher at low discharge. However, if the net energy budget was negative (losing heat), the 7DADM was lower at low discharge. Effective shade thresholds ranging from 50% to 65% determined if the stream was gaining or losing heat. Above this threshold, scenarios with high discharge (+30%) are actually warmer than those with low discharge (−30%) (Figure 7a). The interactions between air temperature and shade are more or less uniform, generally leading to a consistent increase in 7DADM over all shade scenarios examined irrespective of location along the study segment (Figure 7b).

The influence of changing discharge or air temperature was always small relative to the influence of effective shade. For example, considering average conditions in the lower 15 km of our study segment, changing discharge from −30% to +30% changed the 7DADM by 1.1°C, or by about the same amount as would a 8.6% change in shade. This 60% change in discharge is very large, however, relative to changes forecast under climate change scenarios, and yet it only produces a small

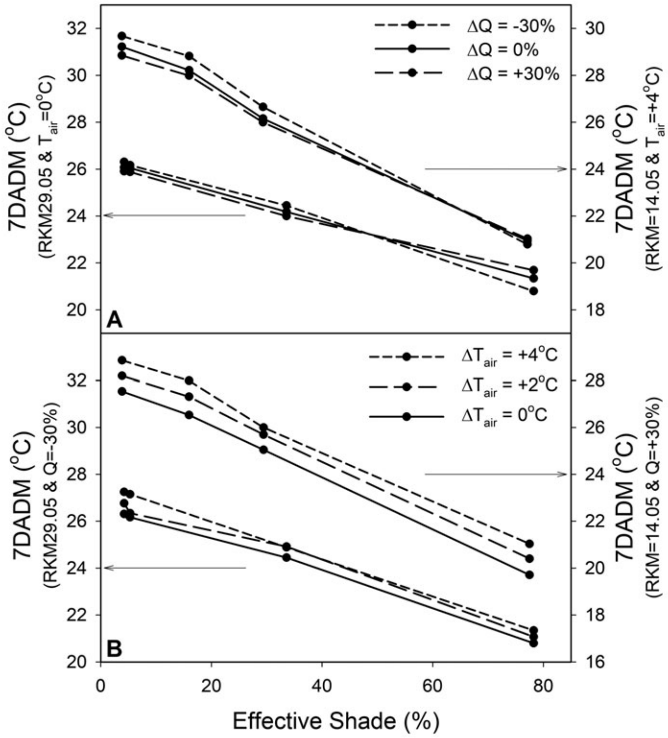

FIGURE 7. Interactive effects of either (a) stream discharge or (b) air temperature with shade. (a) Left *y*-axis shows RKM29.05 with T_{air} = 0°C; right *y*-axis shows RKM14.05 with T_{air} = +4°C. (b) Left *y*-axis shows RKM29.05 with −30% *Q*; right *y*-axis shows RKM14.05 with +30% *Q*. Note that the *y*-axes are offset by several degrees, as indicated by thin horizontal arrows pointing to 24°C, to keep lines from overlapping and making the graph difficult to read.

change in the 7DADM. In contrast, an 8% or 9% change in shade is small, relative to the current conditions and the potential of riparian forests to shade the stream. Stream temperatures are slightly more sensitive to changes in air temperature, such that changing air temperatures by 4°C changed stream temperatures as much as a 13% change in effective shade.

DISCUSSION

Model Uncertainties

Uncertainties in simulation results stem from four factors: (1) upstream boundary conditions for the amount and temperature of water entering the study segment, (2) the amount and temperature of lateral inputs from tributaries and groundwater inflows, (3) hyporheic exchange flow, and (4) retaining base-case values for both humidity and wind speed. The time series of water temperatures at the upstream boundary and of lateral inflows was not changed from those of the 2002 base-case conditions with which the model was originally calibrated. Future climate changes could lead to changes in the water temperature at this boundary. However, these temperatures are much more sensitive to changes in shade from riparian vegetation than to changes in air temperature. Above the study segment, long reaches of the upper MFJD flow through open meadows as do the lower reaches of many tributaries. These water sources were relatively hot under current conditions; with increased shade, they could be substantially cooler. Because there is a large range in realistic temperatures for these boundary conditions, retaining the current temperature is a reasonably conservative assumption for our simulations.

We did not change groundwater temperatures in our scenarios. However, as air temperatures increase, groundwater temperatures would also be expected to increase (Meisner et al. 1988). Recharge temperatures are likely quite cold, however, because precipitation comes mostly in the winter with substantial accumulation of snow so that much of the groundwater recharge likely comes from snowmelt. Also, the residence times of the groundwater are unknown so that the lag time before the temperatures of groundwater inflows increase is also unknown. Despite these uncertainties, the relatively high sensitivity of the stream temperature to the lateral inflows suggests that warming groundwater could lead to substantial stream warming sometime in the future.

The influence of hyporheic exchange flow on future stream temperatures was not examined. All simulations held channel morphology constant. Because channel morphology is a primary control of hyporheic exchange in mountain rivers (Kasahara and Wondzell 2003), we would not expect there to be any difference in the influence of the hyporheic zone on stream temperatures among the 36 model scenarios we examined. Further, the relative influence of hyporheic exchange flows on stream temperatures decreases rapidly with stream size (Wondzell 2011), so that this influence would be modest, at best, in a stream the size of the upper MFJD.

We did not have data available from which we could project reasonable future changes in relative humidity or wind speed for the different scenarios. The future climatic data we used, from CIG, did not project likely future changes in either of these parameters. Also, we recognize that these parameters are likely to change substantially with changes in riparian vegetation, especially under our mature forest scenario, where we would expect the forest canopy to substantially reduce wind speeds and potentially increase relative humidity. However, we do not know the likely magnitude of these changes. Thus, we used the 2002 base-case values for both relative humidity and wind speed in all of our 36 scenarios. We know that relative humidity and wind speed have their largest effects on evaporative (latent) and convective heat fluxes. However, these terms have relatively small influences on maximum daily temperatures in summer when the heat budget is dominated by shortwave radiation. Secondly, the influence of increased humidity and decreased wind speed would tend to cancel each other out, because increased humidity would decrease the heat lost to evaporation and at the same time decreased wind speed would tend to decrease convective heat gains (Leach and Moore 2010). Overall, we expect that our choice to use the 2002 base-case conditions for both relative humidity and wind speed in all of the 36 future scenarios we examined had little effect on the results of our simulations.

Comparison between Regression and Heat Budget Approaches

Stream temperature vs. air temperature regression analyses conducted on the Middle Fork John Day (Ruesch et al. 2012), and more broadly (Mantua et al. 2010; van Vliet et al. 2011; Isaak et al. 2012; Mayer 2012; Moore et al. 2013; Luce et al. 2014) consistently show that increases in air temperature predicted by downscaled GCM outputs will lead to significant stream warming in the future. Studies using mechanistic models report somewhat similar results (Chen et al. 1998; Cristea and Burges 2010; Lawrence et al. 2014; this paper). However, the regression approaches consistently identify air temperature as the single most important determinant of future increases in stream temperature, with factors such as stream discharge, baseflow index, stream slope or proportion of forested area having much weaker correlation with the observed sensitivity of streams to air temperatures (Kelleher et al. 2012; Mayer 2012; Moore et al. 2013; Luce et al. 2014). These relationships, however, are based on the correlation structure within a given dataset and as such, cannot directly identify causal factors.

Luce et al. (2014) argued that direct convective heat transfer from the atmosphere to the stream surface is small and instead suggested that changing air temperature and atmospheric emissivity would lead to net increases in longwave radiation to the stream, thus explaining the strong relationship between air temperatures and stream temperatures. Our analysis of the heat budget in scenarios with warmer air temperatures tends to support their conclusion. If discharge and riparian vegetation do not change and air temperature is 4°C warmer, the change in the net longwave radiation substantially reduces the amount of heat dissipated from the stream, becoming the largest single factor contributing to stream warming (Figures 5 and 6). Atmospheric conditions were not changed in any of the modeled scenarios, thus emissivity remained constant over all simulations. And while increased emissivity could lead to relatively larger changes in net longwave radiation as described by Luce et al. (2014), the hottest days of the year tend to occur on clear summer days when atmospheric emissivity is likely to be low.

Regression analyses of the relationship between stream and air temperature usually suggest that direct convective heat exchange with the warmer air will be a very small term in the energy budget. Our heat budget analysis does not entirely support this conclusion. The second largest change in the stream's energy budget came from convection in scenarios where neither riparian vegetation nor stream discharge changed, and thus contributed substantially to stream warming. Evaporative cooling also increased; however, this heat flux was small, relative to changes in net longwave radiation and convection.

Many papers reporting the results of regression analyses between air and stream temperatures also report that RMSE of the final fitted models are quite high, and often attribute these to local factors that cannot be included in analyses of many sites spanning large geographic extents. Riparian shade is the most frequently identified local factor that would limit the fit between air and stream temperatures. This is well supported by our model results which clearly show that the influence of riparian vegetation on shortwave radiation is the largest single term influencing future stream temperatures.

Future Thermal Regimes Under a Warmer Climate

Our simulation results suggested that the upper Middle Fork John Day has a wide range of potential future stream temperatures. Specifically, estimates of the future 7DADM range from 2.9°C warmer to 7.6°C cooler than current conditions under a future climate in which air temperatures are 4°C hotter than today.

Shade was by far and away the single biggest factor influencing future stream temperatures — as previously demonstrated in similar studies employing mechanistic models (Chen et al. 1998; Cristea and Burges 2010; Lawrence et al. 2014; Justice et al. 2017). Under current conditions, there is relatively little shade from riparian vegetation, so disturbances that remove shade have small effects, but can interact with increases in air temperature to substantially increase maximum water temperatures. Conversely, if little shade is currently available, then there must be long lengths of stream where growing riparian forests to shade the stream may have a potentially huge influence on future thermal regimes. This was borne out in our Heat Source simulations. Increasing shade by growing riparian forests that were 30 m tall with 50% canopy cover reduced maximum stream temperatures well below current temperatures, even under warmer future climatic conditions.

Given the potential importance of shade to future stream thermal regimes, a critical question then becomes — *Is it realistic to grow extensive riparian forests to shade this, or similar, stream reaches and thereby substantially reduce future maximum summer temperatures?* The current conditions of the channel and riparian forest along the upper MFJD are far different than their conditions prior to Euro-American settlement (Wissmar et al. 1994; also see description under Study Site). Historic conditions were more complex, especially in stream reaches with wide, or unconstrained, valley floors. These reaches have been converted from sinuous, multi-thread channels to straighter, single-thread channels. Historic vegetation in these reaches included conifer forest, hardwood forest, woody riparian shrubs, and wet meadows, whereas today most of these reaches support dry meadows with substantial cover of introduced European pasture grasses. The effect of the change from historical to current conditions on stream thermal regimes is likely to have been complex. For example, increased sinuosity, multi-thread channels, and the likely presence of beaver ponds on some back channels would all increase the stream surface area, increase total channel length, and decrease flow velocity so that a greater surface area of water would be exposed to sunlight over a longer period of time, potentially leading to warmer summer stream temperatures than occur today. However, multi-thread channels and channel sinuosity would promote hyporheic exchange, narrower multi-thread channels would be more completely shaded by tall riparian shrubs, and channels might be narrower and deeper — all of which would promote cooler water temperatures.

Clearly, neither the dry meadow vegetation nor the relatively straight single-thread channels are representative of historical conditions. Given these large changes relative to historical conditions, restoration efforts might have substantial leeway to explore alternative desired future conditions. For example, wet meadows may have once been common, but in most places today, the valley floor has been drained. The resulting dry meadow complexes have site characteristics that are likely to support a variety of riparian woody vegetation dominated by conifers and hardwoods that would effectively shade the stream. This potential has been widely recognized and major investments have been made to replant a variety of native riparian trees and shrubs throughout the upper Middle Fork John Day, and elsewhere throughout the interior Columbia Basin.

Our simulation scenarios specifically examined these restoration treatments. We used a simple approach, examining uniform vegetation growing over the entire riparian zone along the full 37-km length of our study segment. We recognize that it is unrealistic to grow and maintain uniform riparian forests over such a long stream reach. We also recognize that restoring forested riparian conditions will not be a simple task. A myriad of issues will need to be addressed. These include decisions whether to plant native species adapted to current conditions or to attempt to restore channels and floodplains and plant species adapted to the restored conditions and whether to modify that selection for species that might be better adapted to presumed future conditions given the effects of climate change (Perry et al. 2015). Also, successful reestablishment of planted native woody species might be difficult due to competition with invasive species, mortality due to the effects of browsing from domestic livestock, deer, and elk (Averett et al. 2017), and cutting of trees by beaver. Further, the growth rates of trees will be dependent on the species and the environmental conditions in which they grow. These will all be critical factors to consider in planning restoration projects. However, the results of our model simulations clearly show that, in streams where shade is currently limited, restoring riparian forest can offset the effect of future increases in air temperature and decreases in stream discharge.

We did not specifically analyze changes in thermal regimes in streams that are currently well shaded. However, comparing mature riparian forest scenarios under base case and +4°C air temperature scenarios suggests that increases in air temperatures would increase stream temperatures in streams that are currently well shaded, a result that agrees well with Woltemade and Hawkins (2016). Further, we would expect that disturbances, such as wildfire, that can substantially reduce shade could lead to large increases in stream temperatures if shade was removed over large segments of a stream's length.

Effects of Changing Discharge in Warming vs. Cooling Streams

The influence of stream discharge on stream temperatures varies, depending on whether the stream is gaining or losing heat, which in our simulations is strongly controlled by effective shade (Figure 7a). Under low shade conditions, the stream was warming and simulated maximum stream temperatures were higher at low discharge than at high discharge. This relationship reversed under high shade conditions in which the stream was cooling so that simulated maximum stream temperatures were actually lower at low discharge than at high discharge. This result can be explained by two factors: (1) how large is the change in the heat budget and (2) how much water must be heated or cooled. For a fixed amount of heat gained or lost, the observed temperature change will be inversely proportional to the amount of water that will be heated or cooled. Much of the scientific literature and management application of that literature concerns warming of streams when they are exposed to increased heat fluxes. Under these conditions, the general rule of thumb — that smaller streams will warm more than larger streams — generally holds true. However, streams are not always warming. For example, under the mature forest scenarios, the stream was losing heat over most of the study segment and the downstream temperatures were substantially cooler than the upstream temperatures. Under these conditions, higher discharge at the head of the study segment meant that more heat needed to be dissipated and thus, the stream cooled more slowly.

We observed “cross-over points” with threshold values of effective shade ranging from 50% to 65% (Figure 7a). When effective shade was below the threshold, the stream was cooler at high discharge; when effective shade was above the threshold, the opposite occurred. The specific value of effective shade at which this “cross-over” occurs will be determined by the specific conditions in any given stream reach. It just so happened that, in our simulations, the streams net energy budget was positive if effective shade was less than ~50% to 65% and negative if effective shade was greater than this. While this general relationship will hold true in any stream, there is no a priori way to know the conditions under which a specific stream reach will either be gaining or losing heat. However, this result can be generalized.

Streams do not consistently warm as they flow downstream. Some reaches will be cooling, others will be warming. Further, these relationships will change between night and day, among days with different weather patterns, and among seasons. The conditions that either tend to promote large heat fluxes per unit volume of water, or decrease the volume of water, will make the stream’s temperature change more quickly. Thus, not only will shallow, wide streams with slow flow velocities and low discharge warm more quickly when they are heated but they will also cool more quickly when they are chilled. Thus, in places where streams flow from long unshaded reaches into densely shaded reaches, the heat budget of the reach could be consistently negative (i.e., the stream is cooling) on hot summer days. In this case, restoration efforts that deepen and narrow the channel, increase flow velocity, or increase discharge, will actually result in a warmer stream.

Overall, our simulation results showed that maximum daily stream temperatures (the 7DADM) were not sensitive to even relatively large changes in stream discharge. Thus, projects that are specifically designed to mitigate high stream temperatures are likely to see greater reductions in stream temperature from restoring riparian vegetation to shade stream reaches where shade is currently limiting than from increasing baseflow stream discharge.

CONCLUSIONS

Our study suggests that restoring riparian vegetation where streams are poorly shaded can offset the influence of projected increases in air temperature and reduced stream discharge under a changing climate. Stream temperatures are far more sensitive to changes in shade than to changes in either air temperature or stream discharge. Because many streams supporting cold water-dependent species through the interior western U.S. have been anthropogenically altered in ways that have substantially reduced shade, there is great potential to restore shade over long segments of these streams. The effect of such restoration could be so large that future stream temperatures could be colder than today, even under a warmer climate with substantially lower late-summer streamflow.

ACKNOWLEDGMENTS

We thank the U.S. Forest Service Pacific Northwest (USFS PNW) Research Station and the U.S. Geological Survey for funds provided through joint venture agreement 10-JV-11261991-055 to Oregon State University; Julia Crown and Ryan Mechie from Oregon Department of Environmental Quality who provided the TMDL reports and monitoring records; the Confederated Tribes of the Warm Springs who provided support for field work and access to the study area, especially Brian Cochran and Steph Charette; and Andrew Gray of the USFS PNW Research Station for querying the FIA database for tree heights. Finally, we thank the Oregon Watershed Enhancement Board, the North Fork John Day Watershed Council, and the John Day Intensively Monitored Watershed for their support. Data describing projected changes in climate were downloaded from the Columbia Basin Climate Change Scenarios Project website at http://warm.atmos.washington.edu/2860/. These materials were produced by the Climate Impacts Group at the University of Washington in collaboration with the Washington State Department of Ecology, Bonneville Power Administration, Northwest Power and Conservation Council, Oregon Water Resources Department, and the B.C. Ministry of the Environment.

LITERATURE CITED

Arismendi, I., S.L. Johnson, J.B. Dunham, and R. Haggerty. 2013. "Descriptors of Natural Thermal Regimes in Streams and Their Responsiveness to Change in the Pacific Northwest of North America." *Freshwater Biology* 58: 880–94.

Arismendi, I., S.L. Johnson, J.B. Dunham, R. Haggerty, and D. Hockman-Wert. 2012. "The Paradox of Cooling Streams in a Warming World: Regional Climate Trends Do Not Parallel Variable Local Trends in Stream Temperature in the Pacific Continental United States." *Geophysical Research Letters* 39: L10401. https://doi.org/10.1029/2012GL051448.

Arismendi, I., M. Safeeq, J.B. Dunham, and S.L. Johnson. 2014. "Can Air Temperature Be Used to Project Influences of Climate Change on Stream Temperature?" *Environmental Research Letters* 9: 08401. https://doi.org/10.1088/1748-9326/9/8/084015.

Averett, J.P., B.A. Endress, M.M. Rowland, B.J. Naylor, and M.J. Wisdom. 2017. "Wild Ungulate Herbivory Suppresses Deciduous Woody Plant Establishment Following Salmonid Stream Restoration." *Forest Ecology and Management* 391: 135–44.

Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb, K.K. Bartz, and H. Imaki. 2007. "Projected Impacts of Climate Change on Salmon Habitat Restoration." *Proceedings of the National Academy of Sciences of the United States of America* 104: 6720–25.

Beschta, R.L. 2000. "Watershed Management in the Pacific Northwest: The Historical Legacy." In *Land Stewardship in the 21st Century: The Contributions of Watershed Management*. COUSDA Forest Service Proceedings RMRS-P-13, edited by P.F. Ffolliott, M.B. Baker, Jr., C.B. Edminster, M.C. Dillon, and K.L. Mora (Tech. Coordinators), 109–16. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Beschta, R.L., and W.J. Ripple. 2005. "Rapid Assessment of Riparian Cottonwood Recruitment: Middle Fork John Day River, Northeastern Oregon." *Ecological Restoration* 23: 150–56.

Boyd, M., and B. Kasper. 2003. "Analytical Methods for Dynamic Open Channel Heat and Mass Transfer: Methodology for Heat Source Model Version 7.0." https://www.oregon.gov/deq/FilterDocs/heatsourcemanual.pdf.

Boyd, M.S. 1996. "Heat Source: Stream, River, and Open Channel Temperature Prediction." MS thesis, Oregon State University.

Bureau of Reclamation. 2008. "Middle Fork and Upper John Day River Tributary Assessments, Grant County, Oregon." http://www.usbr.gov/pn//fcrps/habitat/projects/johnday/reports/tributaryassmt/midfortk-jdas2008.pdf.

Chen, Y.D., S.C. McCutcheon, D.J. Norton, and W.L. Nutter. 1998. "Stream Temperature Simulation of Forested Riparian Areas: II. Model Application." *Journal of Environmental Engineering* 124: 316–28.

Cristea, N.C., and S.J. Burges. 2010. "An Assessment of the Current and Future Thermal Regimes of Three Streams Located in the Wenatchee River Basin, Washington State: Some Implications for Regional River Basin Systems." *Climatic Change* 102: 493–520.

Crown, J., and D. Butcher. 2010. *John Day River Basin Total Maximum Daily Load (TMDL) and Water Quality Management Plan (WQMP)*. Portland, OR: Oregon Department of Environment.

Diabat, M. 2014. "The Influence of Climate Change and Restoration on Stream Temperature." PhD dissertation, Oregon State University.

Diabat, M., R. Haggerty, and S.M. Wondzell. 2012. "Diurnal Timing of Warmer Air Under Climate Change Affects Magnitude, Timing and Duration of Stream Temperature Change." *Hydrological Processes* 27: 2367–78.

Donnegan, J., S. Campbell, and D. Azuma. 2008. *Oregon's Forest Resources, 2001–2005: Five-Year Forest Inventory and Analysis Report*. PNW-GTR-765. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.

Dunham, J.B., A.E. Rosenberger, C.H. Luce, and B.E. Rieman. 2007. "Influences of Wildfire and Channel Reorganization on Spatial and Temporal Variation in Stream Temperature and the Distribution of Fish and Amphibians." *Ecosystems* 10: 335–46.

Federal Caucus. 2000. *Conservation of Columbia Basin Fish, Final Basinwide Salmon Recovery Strategy* (Volumes 1–2). Portland, OR. http://www.salmonrecovery.gov/Files/BiologicalOpinions/2000/2000_Final_Strategy_Vol_1.pdf; http://www.salmonrecovery.gov/Files/BiologicalOpinions/2000/2000_Final_Strategy_Vol_2.pdf.

GAO. 2002. "Columbia River Basin Salmon and Steelhead: Federal Agencies' Recovery Responsibilities, Expenditures and Actions." Government Accounting Office, GAO Report #GAO-02-612. https://www.gao.gov/assets/240/235262.pdf.

Garner, G., I.A. Malcolm, J.P. Sadler, C.P. Millar, and D.M. Hannah. 2015. "Inter-Annual Variability in the Effects of Riparian Woodland on Micro-Climate, Energy Exchanges and Water Temperature of an Upland Scottish Stream." *Hydrological Processes* 29: 1080–95.

Gleick, P.H. 1986. "Methods for Evaluating the Regional Hydrologic Impacts of Global Climatic Changes." *Journal of Hydrology* 88 (1–2): 97–116. https://doi.org/10.1016/0022-1694(86)90199-X.

Gomi, T., R.D. Moore, and A.S. Dhakal. 2006. "Headwater Stream Temperature Response to Clear-Cut Harvesting with Different Riparian Treatments, Coastal British Columbia, Canada." *Water Resources Research* 42: W08437. https://doi.org/10.1029/2005WR004162.

Gregory, S.V., and P.A. Bisson. 1997. "Degradation and Loss of Anadromous Salmonid Habitat in the Pacific Northwest." In *Pacific Salmon & Their Ecosystems*, edited by D.J. Stouder, P.A. Bisson, and R.J. Naiman, 277–314. Boston, MA: Springer.

Hamlet, A.F., P. Carrasco, J. Deems, M.M. Elsner, T. Kamstra, C. Lee, S.-Y. Lee, G. Mauger, E.P. Salathe, I. Tohver, and L. Whitely Binder. 2010. "Final Project Report for the Columbia Basin Climate Change Scenarios Project." http://warm.atmos.washington.edu/2860/report/.

Hamlet, A.F., M.M. Elsner, G. Mauger, S.-Y. Lee, and I.M. Tohver. 2013. "An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results." *Atmosphere-Ocean* 51: 392–415.

Hay, L.E., R.L. Wilby, and G.H. Leavesley. 2000. "A Comparison of Delta Change and Downscaled GCM Scenarios for Three Mountainous Basins in the United States." *Journal of the American Water Resources Association* 36 (2): 387–97. https://doi.org/10.1111/j.1752-1688.2000.tb04276.x.

Hicks, M. 2000. "Evaluating Standards for Protecting Aquatic Life in Washington's Surface Water Quality Standards: Temperature Criteria." Draft Discussion Paper and Literature Summary. Publication #00-10-070. Revised 2002, 189 pp. Olympia, WA: Washington State Department of Ecology.

Hilderbrand, R.H., M.T. Kashiwagi, and A.P. Prochaska. 2014. "Regional and Local Scale Modeling of Stream Temperatures and Spatio-Temporal Variation in Thermal Sensitivities." *Environmental Management* 54: 14–22.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. Cambridge University Press, Cambridge, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Isaak, D.J., S. Wollrab, D. Horan, and G. Chandler. 2012. "Climate Change Effects on Stream and River Temperatures across the

Northwest U.S. from 1980–2009 and Implications for Salmonid Fishes." *Climatic Change* 113: 499–524.
Janisch, J.E., S.M. Wondzell, and W.J. Ehinger. 2012. "Headwater Stream Temperature: Interpreting Response after Logging, with and without Riparian Buffers, Washington, USA." *Forest Ecology and Management* 270: 302–13.
Johnson, S.L. 2004. "Factors Influencing Stream Temperatures in Small Streams: Substrate Effects and a Shading Experiment." *Canadian Journal of Fisheries and Aquatic Sciences* 61: 913–23.
Justice, C., S.M. White, D.A. McCullough, D.S. Graves, and M.R. Blanchard. 2017. "Can Stream and Riparian Restoration Offset Climate Change Impacts to Salmon Populations?" *Journal of Environmental Management* 188 (2017): 212–27.
Kasahara, T., and S.M. Wondzell. 2003. "Geomorphic Controls on Hyporheic Exchange Flow in Mountain Streams." *Water Resources Research* 39 (1): 1005. https://doi.org/10.1029/2002WR001386.
Kelleher, C., T. Wagener, M. Gooseff, B. McGlynn, K. McGuire, and L. Marshall. 2012. "Investigating Controls on the Thermal Sensitivity of Pennsylvania Streams." *Hydrological Processes* 26: 771–85.
Lawrence, D.J., B. Stewart-Koster, J.D. Olden, A.S. Ruesch, C.E. Torgersen, J.J. Lawler, D.P. Butcher, and J.K. Crown. 2014. "The Interactive Effects of Climate Change, Riparian Management, and a Non-Native Predator on Stream-Rearing Salmon." *Ecological Applications* 24: 895–912.
Leach, J.A., and R.D. Moore. 2010. "Above-Stream Microclimate and Stream Surface Energy Exchanges in a Wildfire-Disturbed Riparian Zone." *Hydrological Processes* 24: 2369–81.
Liang, X., D.P. Lettenmaier, and E.F. Wood. 1996. "One-Dimensional Statistical Dynamic Representation of Subgrid Spatial Variability of Precipitation in the Two-Layer Variable Infiltration Capacity Model." *Journal of Geophysical Research* 101: 21403–22. https://doi.org/10.1029/96JD01448.
Luce, C., B. Staab, M. Kramer, S. Wenger, D. Isaak, and C. McConnell. 2014. "Sensitivity of Summer Stream Temperatures to Climate Variability in the Pacific Northwest." *Water Resources Research* 50: 3428–43.
Mantua, N., I. Tohver, and A. Hamlet. 2010. "Climate Change Impacts on Streamflow Extremes and Summertime Stream Temperature and Their Possible Consequences for Freshwater Salmon Habitat in Washington State." *Climatic Change* 102: 187–223.
Mayer, T.D. 2012. "Controls of Summer Stream Temperature in the Pacific Northwest." *Journal of Hydrology* 475: 323–35.
McCullough, D.A., J.M. Bartholow, H.I. Jager, R.L. Beschta, E.F. Cheslak, M.L. Deas, J.L. Ebersole, J.S. Foott, S.L. Johnson, K.R. Marine, and M.G. Mesa. 2009. "Research in Thermal Biology: Burning Questions for Coldwater Stream Fishes." *Reviews in Fisheries Science* 17 (1): 90–115.
McCullough, D.A., S. Spalding, D. Sturdevant, and M. Hicks. 2001. "Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids." Issue Paper 5. EPA-910-D-01-005. United States Environmental Protection Agency, Region 10, 114 pp.
Meisner, J.D., J.S. Rosenfeld, and H.A. Regier. 1988. "The Role of Groundwater in the Impact of Climate Warming on Stream Salmonines." *Fisheries* 13 (3): 2–8.
Mohseni, O., T.R. Erickson, and H.G. Stefan. 1999. "Sensitivity of Stream Temperatures in the United States to Air Temperatures Projected Under a Global Warming Scenario." *Water Resources Research* 35: 3723–33.
Mohseni, O., and H.G. Stefan. 1999. "Stream Temperature/Air Temperature Relationship: A Physical Interpretation." *Journal of Hydrology* 218: 128–41.
Moore, R.D., M. Nelitz, and E. Parkinson. 2013. "Empirical Modelling of Maximum Weekly Average Stream Temperature in British Columbia, Canada, to Support Assessment of Fish Habitat Suitability." *Canadian Water Resources Journal* 38: 135–47.
Moore, R.D., D.L. Spittlehouse, and A. Story. 2005. "Riparian Microclimate and Stream Temperature Response to Forest Harvesting: A Review." *Journal of the American Water Resources Association* 41: 813–34.
Nehlsen, W., J.E. Williams, and J.A. Lichatowich. 1991. "Pacific Salmon at the Crossroads: Stocks at Risk from California, Oregon, Idaho and Washington." *Fisheries* 16: 4–21.
ODEQ. 2008. "Temperature and Water Quality Standard Implementation." Oregon Department of Environmental Quality (ODEQ). https://www.oregon.gov/deq/Filtered%20Library/IMDTemperature.pdf.
ODEQ. 2010. "John Day River Basin Total Maximum Daily Load (TMDL) and Water Quality Management Plan (WQMP)." Oregon Department of Environmental Quality (ODEQ). https://www.oregon.gov/deq/wq/tmdls/Pages/TMDLs-Basin-John-Day.aspx.
Perry, L.G., L.V. Reynolds, T.J. Beechie, M.J. Collins, and P.B. Shafroth. 2015. "Incorporating Climate Change Projections Into Riparian Restoration Planning and Design." *Ecohydrology* 8: 863–79.
Richter, A., and S.A. Kolmes. 2005. "Maximum Temperature Limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest." *Reviews in Fisheries Science* 13 (1): 23–49. https://doi.org/10.1080/10641260590885861.
Rieman, B.E., C.L. Smith, R.J. Naiman, G.T. Ruggerone, C.C. Wood, N. Huntly, E.N. Merrill, J.R. Alldredge, P.A. Bisson, J. Congleton, K.D. Fausch, C. Levings, W. Pearcy, D. Scarnecchia, and P. Smouse. 2015. "A Comprehensive Approach for Habitat Restoration in the Columbia Basin." *Fisheries* 40 (3): 124–35.
Ruesch, A.S., C.E. Torgersen, J.J. Lawler, J.D. Olden, E.E. Peterson, C.J. Volk, and D.J. Lawrence. 2012. "Projected Climate-Induced Habitat Loss for Salmonids in the John Day River Network, Oregon, U.S.A." *Conservation Biology* 26: 873–82.
Sinokrot, B.A., H.G. Stefan, J.H. McCormick, and J.G. Eaton. 1995. "Modeling of Climate Change Effects on Stream Temperatures and Fish Habitats Below Dams and Near Groundwater Inputs." *Climatic Change* 30: 181–200.
van Vliet, M.T.H., F. Ludwig, J.J.G. Zwolsman, G.P. Weedon, and P. Kabat. 2011. "Global River Temperatures and Sensitivity to Atmospheric Warming and Changes in River Flow." *Water Resources Research* 47: W02544. https://doi.org/10.1029/2010WR009198.
Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. "Warming and Earlier Spring Increases Western U.S. Forest Wildfire Activity." *Science* 313: 940–43.
Wissmar, R.C., J.E. Smith, B.A. McIntosh, H.W. Li, G.H. Reeves, and J.R. Sedell. 1994. "A History of Resource Use and Disturbance in Riverine Basins of Eastern Oregon and Washington (Early 1800s–1900s)." *Northwest Science* 68 (Special Issue): 1–35.
Woltemade, C.J., and T.W. Hawkins. 2016. "Stream Temperature Impacts Because of Changes in Air Temperature, Land Cover and Stream Discharge: Navarro River Watershed, California, USA." *River Research and Applications* 32: 2020–31.
Wondzell, S.M. 2011. "The Role of the Hyporheic Zone across Stream Networks." *Hydrological Processes* 25: 3525–32.