Technical Memorandum for CWR Report

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To: Cold Water Refugia Report Project Team
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Subject: Stream temperature predictions under varying shade and climate scenarios in the Columbia River basin

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Abstract - This technical memorandum briefly explains the goals, approach, results, and conclusions for a stream temperature modeling effort conducted in the tributaries that flow into the Columbia River downstream of the Snake River confluence (the project scope for the EPA Cold Water Refugia Project). ***The purpose of these modeling exercises was to explore how stream temperatures change under varying levels of reach shade and climate, but with a focus on the potential benefit (stream cooling) from restoring riparian vegetation shading across the study region.*** The analysis, therefore, provides some insight on the spatial and temporal availability of cold-water habitat in tributaries of the Columbia River for Pacific salmon. We used spatial stream network (SSN) models to predict mean August stream temperatures for nine different scenarios that contrasted three levels of reach shading with three different climates. The three shade levels represented (1) topographic shade (no riparian vegetation and theoretical worst-case-scenario for shade), (2) current riparian vegetation, and (3) restored riparian vegetation (theoretical best-case-scenario for shade). We also used three climate scenarios that represented climate conditions for (1) the "present" (derived from an historical average from 1993-2011), (2) the 2040s decade, and (3) the 2080s decade. Across the study region, our models predicted mean August riparian shade restoration stream temperatures (under the present climate scenario) to be on average 0.5°C (± 0.39SD) cooler than current vegetation shade steam temperatures. Streams that were predicted to cool the most between current and restored riparian vegetation scenarios were generally smaller streams with bank-full widths of 5m or less. Additionally, the mainstem Columbia River tributaries are predicted to reach the mainstem river on average (flow-weighted) by 0.4°C (± 0.24SD) cooler than they are currently under the same restoration conditions (current versus restored riparian shade for the present climate). Lastly, the stream warming predicted by the 2040s at these tributary outflows to the mainstem Columbia River could be reduced by about half if full riparian shade restoration is implemented across the study region. However, the feasibility of this large-scale restoration effort is not likely, so additional restoration options to cool streams should also be undertaken to help maintain stream temperatures near their current condition.

Introduction

Pacific salmon require cold-water habitat to complete the part of their life cycle that occurs in freshwater systems. A key stage of their life cycle in freshwater includes upstream movements to headwater streams where spawning occurs. When these migrations occur during peak summer temperatures, continuous or distributed patches of cold-water habitat are necessary for these species to survive and reach their spawning grounds (Bjorn and Reiser 1991, Strange 2010). Aquatic thermal regimes have been altered and probably made warmer due to human activity (land use change and hydromodification – damming/diversions) and changes in climate (Hatcher and Jones 2013). Consequently, the availability of suitable cold-water habitat may already be reduced and is believed to become more vulnerable in the future. Because of these impacts, it is important, for the viability of Pacific salmon, to understand where suitable habitat exists, how that habitat might change in the future, and if restoration efforts to cool streams are useful management options moving forward.

The Columbia River basin is a system that is both heavily used by Pacific Salmon, but also heavily impacted by human modifications to the landscape and river network (Hatcher and Jones 2013). The upland landscape ranges from intense agriculture (e.g., Willamette Valley and Yakima Valley) to heavily managed timberlands interspersed with patches of pristine old growth forest (e.g., Mt. Hood, Willamette, and Deschutes National Forests), while major in-stream impacts result from the numerous dams built across the river network, as well as past snagging and channelization that have simplified habitats. To address the decline and loss of cold-water habitat for Pacific Salmon from these impacts, identifying and strategically locating restoration efforts with the potential to improve stream temperatures is useful for wildlife and conservation managers.

Fortunately, water temperature has been recognized, since some of the earliest investigations of ecosystems (Lindeman 1942), as a master variable (Minshall 1988) controlling ecosystem processes, species life history traits, and biotic interactions (Caissie 2006). Because temperature is such an important mechanistic variable for a diverse set of ecosystem parameters, decades of research has been conducted to investigate what controls (and then to predict) water temperature in aquatic systems at small and large spatial extents (Brown 1969, Poole and Berman 2001, Isaak et al. 2017). While classification of stream thermal regimes and their primary controlling mechanisms has been difficult due to complex interactions at various spatial extents (Poole and Berman 2001, Caissie 2006), solar radiation has long been acknowledged as an important thermal budget component for any stream reach (Brown and Krygier 1970). Therefore, controlling the solar radiation component of a stream reach should be a primary target for thermal restoration of a stream. In practice, this restoration technique (increasing riparian shade along stream reaches) has been successful for reducing stream temperatures locally (Beschta 1997). However, the implementation of large-scale riparian restoration across large spatial extents (regions or entire drainage basins) has not been employed.

Since experimental manipulations at very large spatial extents are generally unrealistic, predictive modeling exercises are the best tools to assess what magnitude effect restoration efforts might produce (Seixas et al. 2017). Therefore, we designed a statistical modeling approach to assess how manipulating riparian vegetation shade affects stream temperature predictions. ***The specific goal of our modeling effort was to identify how much stream temperatures change (locally and regionally) when manipulating riparian vegetation shade across large spatial extents under different climate conditions.*** The predictive modeling approach undertaken for this research used geospatial representations of covariates that have known effects on stream temperature and statistical Spatial Stream Network (SSN) models (Peterson and Ver Hoef 2010, Isaak et al. 2017). SSN models were designed to specifically address the spatial autocovariance unique to river network dendritic morphology and the influence of water flow (Peterson and Ver Hoef 2010). This makes them an ideal statistical modeling tool for this type of research. Our model predictions (of stream temperature) for the varying riparian shade and different climate levels can then be used to investigate the potential benefit from riparian shade restoration (or loss) across tributaries of the Columbia River basin for Pacific Salmon in present and future climates.

1 Methods

To address the potential for riparian shade restoration to cool streams, mean August stream temperatures were modelled for nine difference scenarios for tributaries across the lower half of the Columbia River network. These nine scenarios are the result of a full cross between two factors (shade and climate; each with three levels of variation) that control stream temperature. Climate input variables (mean August air temperature and discharge) were manipulated to represent climates associated with a recent historical baseline (1993 to 2011) that we are labelling as the "present" climate. Future climates also modify these input parameters to represent the 2040s, and the 2080s. Riparian shade was an input parameter that represented three levels of reach shade (measured as the proportion of the stream reach that is shaded). These shade levels included a landscape with no riparian vegetation for shading (topographic shading only), the current riparian vegetation shading, and the potential restored vegetation shading in the system (Table 1). Current and restored vegetation shading also incorporate topographic shading into their estimates. The purpose of including the topographic shade level is to have the "worst-case" scenario, as though all riparian buffers were removed from stream banks. A comparison between topographic and current vegetation levels offers some insight into how much riparian habitat is already missing, how much more riparian vegetation across the study region could be lost, and what that might mean for stream temperature.

Table 1. Scenarios for cross between three climate and three shade levels.

CLIMATE LEVELS	**SHADE LEVELS**		
	Topographic (No Vegetation)	Current (2014) Vegetation	Restored Vegetation
Present	*Topo./Present*	*Current/Present*	*Restored/Present*
2040s	*Topo./2040*	*Current/2040*	*Restored/2040*
2080s	*Topo./2080*	*Current/2080*	*Restored/2080*

1.1 Model description

A spatial stream network (SSN) model was used to predict mean August stream temperatures for a portion of the Columbia River network (Figure 1). The model was modified from the published NorWeST mean August stream temperature SSN models developed for the Oregon Coast (OR Coa.) and Mid-Columbia (Mid-Col.) processing units (Isaak et al. 2017) that together encompass the entire study region. Included in these NorWeST SSN models are 12 prediction variables (Table 2). Original NorWeST data were used for 11 of these parameters but the *canopy shading* variable was replaced with current shade data generated for this study (see **Vegetation shading** section). Besides this data substitution, no other changes were made to the NorWeST models for these two processing units. This includes no additional model selection procedures that would result in the removal of insignificant parameters once the models are refit with the new shade data. This was done to remain consistent with the original NorWeST model for each processing unit. Additionally, it should be noted, that the NorWeST model for the Mid-Columbia processing unit did not include the parameter describing the proportion of area covered in glaciers because no glaciers are present in this processing unit study area.

The NorWeST models were refit in each of the two processing units (Oregon Coast and Mid-Columbia) with the new shade covariate. Predictions of stream temperatures across the study area used historical data for mean August air temperature and discharge averaged across the time period of 2003-2011 (as in the NorWeST model). This historical average prediction is what this study calls the “present” climate scenario as it best represents the present climate conditions. These model fits were then used to predict across the eight remaining model scenarios by substituting mean August air temperature and discharge data to represent the different climates, while substituting reach shade data for each stream segment to account for differences in shade levels.

1.2 Vegetation shading

To develop the new shade covariate, we used the “Shade.xls” model to predict mean August stream shade for tributaries that drain into Columbia River within the Oregon Coast and Mid-Columbia processing units. This model has been used for 20 years in Total Maximum Daily Load (TMDL) development by the Washington Department of Ecology, Idaho Department of Environmental Quality, and Oregon Department of Environmental Quality and obtained from the Washington Department of Ecology Water Quality Models website (ecology.wa.gov/Research-Data/Data-resources/Models-spreadsheets/Modeling-the-environment/Models-tools-for-TMDLs). Algorithms to calculated shade in the model come from Chen et al. (1998). Shade model input parameters were derived from freely available (online) GIS datasets (Table 3).

1.3 Climate scenarios

Stream temperature scenarios associated with different climate periods follow methods used for the NorWeST regional temperature model (Isaak et al. 2017). Briefly, the three climate levels are generated by setting average predicted August air temperature and stream discharge values to represent predicted changes across the region. The predictions for future climate scenarios were average values from a suite of ten global climate change models for the period of interest in each scenario (2040s and 2080s; Hamlet et al. 2013). For the 2040s future scenario, the average climate values were from 2030 to 2059 and for the 2080s the record was from 2070-2099. The present climate scenario is derived from an historical average of climate variables from 1993 to 2011.

Table 2. NorWeST covariates for predicting mean August stream temperature (Isaak et al. 2016).

Parameter	Abbreviation	Units	Source
Mean August air temperature	airtemp	degree C	Dynamically downscaled NCEP RegCM3 reanalysis (Hostetler et al. 2011; http://regclim.coas.oregonstate.edu/index.html) (15-km or 50-km grid)
Mean August stream discharge	flow	cubic m/s	Averaged across USGS flow gages with long-term records and minimal water abstraction or storage reservoirs (http://watersdata.usgs.gov/nwis/rt)
Elevation	elev	m	National Elevation Dataset (NED) with NHDPlus v2 (30 m grid)
Latitude	lat	m	Derived by snapping agency coordinates to NorWEST stream network
Canopy shade*	canopy	%	2001 National Land Cover Database (MRLC-2001; Homer et al. 2007) modified for 2001-2008 based on USFS burn severity data based on Miller et al. (2009); 2011 NLCD (MRLC-2011, Homer et al. 2015; 30 m grid)
Cumulative drainage area	drainage	square km	NHDPlus v2 (McKay et al. 2012)
Stream slope	slope	%	NHDPlus v2 (McKay et al. 2012)
Mean annual precipitation	precip	mm	NHDPlus v2 (McKay et al. 2012, based on PRISM 1971-2000)
Base flow index	bfi	unitless	http://ks.water.usgs.gov/pubs/abstracts/of.03-263.htm
Glacier proportion	glacier	%	Fountain et al. 2006; http://glaciers.research.pdx.edu/Downloads (1:100,000)
Lake proportion	water	%	NLCD (MRLC-NLCD 2011) in NHDPlus v2 (McKay et al. 2012)
Tailwater	TAILWATER	unitless	Binary variable assigned to indicate whether a stream temperature site was in a reach downstream of a deep reservoir that is anomalously cold due to releases of hypolimnetic waters

* This NorWeST canopy shade data was substituted with new shade data in this study (Section 2.2 Vegetation shading).

Table 3. Derived “Shade.xls” input parameters and GIS datasets.

Parameter	Data sources and methods	Websites
Stream Aspect	Stream line segments (approximately 1 km in length) were obtained from the United States Forest Service NorWeST website. Stream aspect for each segment was derived using the Linear Directional Mean ArcGIS extension.	fs.fed.us/rm/boise/AWAE/projects/NorWeST
Stream Elevation and Topographic Shade Angle	Stream reach midpoints for each stream line segment were obtained from the United States Forest Service NorWeST website. Elevation and Topographic Shade Angle for each midpoint were sampled from the NHDPlus v2 30-meter digital elevation model using the Ttools ArcGIS extension.	horizon-systems.com/nhdplus
Stream Bankfull Width	Stream channel bankfull widths (BFW) were derived for each NorWeST stream line segment from an empirical relationship (Beechie and Imaki 2014) based on upstream watershed area and mean annual precipitation in the upstream watershed. Upstream watershed area was estimated for each stream node using the ArcHydro extension for ArcGIS from the NHDPlus v2 flow direction and the flow accumulation grids (30m resolution). The 30-year normal precipitation data was from the Oregon State University PRISM dataset.	prism.oregonstate.edu/normals
Current and Potential Vegetation Height and Canopy Cover	Vegetation height and canopy cover conditions were sampled from a 36.5m (120ft) buffer surrounding each NorWeST stream line segment. Weighted average current vegetation conditions were derived from the average conditions reported in two GIS datasets downloaded from the Landfire website: 1) Existing Vegetation Height (EVH); and 2) Existing Vegetation Cover (EVC). Weighted average restored vegetation conditions were derived from the Environmental Site Potential (ESP) Landfire GIS dataset, populated with vegetation height and canopy cover targets presented in Oregon Department of Environmental Quality and Washington Department of Ecology TMDL documents.	landfire.gov

1.4 Analysis and statistics

The model fit for each processing unit (Oregon Coast and Mid-Columbia) was evaluated using a few different statistics. These statistics included a Leave One Out Cross Validation (LOOCV) R^2 estimate and Root Mean Square Prediction Error (RMSPE) for the two model fits with new shade data. The LOOCV R^2 statistic describes how much of the observed data variance the model explains while the RMSPE statistic is the estimated model prediction error in degrees Celsius. In addition to these two statistics, the percent variation explained by Fixed Effects and other components (autocovariance functions and random effects) were evaluated for overall model fit behavior. Fixed Effects, in this case, are the main covariates (Table 2) and the other components are the spatially-autocorrelated error functions of those effects as well as any other random blocking covariates (Peterson and Ver Hoef 2010).

Analysis of the model output (temperature predictions) focused on two restoration goals with different spatial extents. First, predicted stream temperatures were evaluated across the entire study region (landscape spatial-extent) to see how much stream temperatures would change as a result of riparian shade manipulation (total loss to complete regrowth). Second, analysis focused on the predicted stream temperatures for tributaries at their confluence with the mainstem Columbia River to determine how well cold-water plumes might be improved or maintained by riparian shade restoration now and in the future.

At the landscape spatial extent, stream temperature prediction scenarios were compared using difference maps (e.g., scenario A temperature predictions minus scenario B temperatures for each segment). These maps highlight where temperature differences were warmer or colder spatially in the landscape between scenarios. Additionally, mean temperature shifts across the landscape were compared to note the overall average temperature change between the scenarios. Furthermore, these spatial temperature shifts were related to other site characteristics, such as bankfull river width, to identify local reach traits related to more or less stream cooling.

At tributary outflows (Figure 1), stream temperatures flowing into the mainstem Columbia River were also compared among scenarios. These comparisons allow some insight into whether restoration in the upstream reaches/tributary network can cool water enough to generate a cold-water refugia plume in the mainstem Columbia River for migrating fish. The temperatures of tributaries were flow-weighted by mean August discharge to identify the mean water temperature entering the mainstem Columbia River for comparison among scenarios. The flow-weights come from current estimates of mean August discharge from the Enhanced Runoff Method used in estimating flow for the NHDPlus v2 data (McKay et al. 2012). These same flow values were used when flow-weighting future scenario temperature means since tributary-specific flow estimates were not available for each tributary outflow. A total of four mean tributary temperatures were calculated for each scenario using different flow-weighting schemes. First, a mean temperature (for all 198 tributaries) was calculated using a flow-weight from all tributaries’ mean August discharge estimates. Second, mean, flow-weighted temperatures for the Oregon Coast tributaries (n = 116) were calculated separately from the Mid-Columbia tributaries. Third, flow-weighted mean temperatures were calculated for just the Mid-Columbia tributaries (n = 82). Finally, a simple average was calculated to estimate mean tributary temperature without any flow weighting for all 198 tributaries.

2 Results and Discussion

The modeling extent for this study region encompassed 78,195 km (30,946.3 km in Oregon Coast; 47,248.4 km in Mid-Columbia processing units) of tributary stream length (excluding the mainstem of the Columbia River) (Figure 1). Only tributaries to the mainstem Columbia River downstream of the Snake River confluence were included in this modeling effort. Within this study extent 10,129 observation sensor deployments (3,140 in Oregon Coast; 6,989 in Mid-Columbia processing units) were used for mean monthly August stream temperature SSN model fitting. These sensors were deployed at a 3,336 locations (1,206 in Oregon Coast; 2,130 in Mid-Columbia processing units) in the study area. Fitting models with “year” as a random effect in the SSN model allows the models to use multiple years of data from a single location which is how these 3,336 sites were able to generate 10,129 observations for the model fitting process. There were 69,961 prediction sites (28,008 in Oregon Coast; 41,953 in Mid-Columbia processing units) approximately evenly spaced (1km stream segments) across the stream network within the study region. Mainstem tributaries (116 in Oregon Coast; 82 in Mid-Columbia processing units) were identified as potentially having August flow (according to NHDPlus v2 EROM attributes; McKay et al. 2012) and therefore being important for August stream temperature prediction (Figure 1). However, most of these tributaries have mean August flows that are quite small (~83% of tributaries have mean August discharges less than 0.5 m^3/s and only ~11% of tributaries have a mean August discharge of 1 m^3/s or larger; see Appendix).

Model fit statistics for the Oregon Coast and Mid-Columbia processing units were similar (Table 4). Both processing unit models had LOOCV R^2 values near 0.9 and RMSPE values less than one degree Celsius (Table 4). These statistics indicate that approximately 90% of the variation in the observed data is accounted for by the model and the error surrounding those observations is less than a degree Celsius. The fixed effects in the models explained a small proportion of the overall variance in the observed temperature data (Oregon Coast: 10.6%; Mid-Columbia: 9%), which indicates that the spatial autocovariance structures used in the models were explaining a large percentage of the variance in the data (Table 4). This is typically the case with particularly dense temperature datasets due to significant redundancy among observations.

Table 4. Model fit statistics for Oregon Coast (OR Coa.) and Mid-Columbia (Mid-Col.) processing units after substituting with new present shade data. Statistics include leave one out cross validation (LOOCV) R^2, root mean square prediction error (RMSPE), percent of variance explained by the fixed effects (Fixed Effects), and the remaining variance not explained by the fixed effects (Other Components).

Proc. Unit	LOOCV R^2	LOOCV RMSPE (C)	Fixed Effects (%)	Other Components (%)
OR Coa.	0.897	0.919	10.6	89.4
Mid-Col.	0.936	0.913	9	91

Estimates for all covariates were significant in the Oregon Coast SSN fit except for *Base Flow Index* and *Mean August Discharge* (Table 5), while in the Mid-Columbia SSN fit, all covariates were significant predictors except for *Tailwater* and *Mean August Discharge* (Table 6). Additionally, in the Mid-Columbia SSN model fit, *Latitude* was only marginally significant (p=0.065) (Table 6).

Table 5. Oregon Coast SSN model parameter raw (Raw) and standardized (Std.) estimates (Est), standard errors (SE), t-statistics (t), and p-values (p). Parameter abbreviations as in Table 2.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p
(Intercept)	1.51e+01	1.76e-01	15.06	0.176	85.5	<<0.001
elev	-5.33e-03	3.14e-04	-3.025	0.178	-16.97	<<0.001
canopy*	-1.52e-02	1.39e-03	-0.935	0.085	-10.95	<<0.001
slope	-6.95e+00	1.08e+00	-0.466	0.073	-6.411	<<0.001
precip	-6.81e-04	1.47e-04	-0.825	0.178	-4.624	<<0.001
drainage	7.02e-06	1.82e-06	0.581	0.15	3.862	<<0.001
lat	-4.88e-06	1.12e-06	-1.27	0.29	-4.372	<<0.001
water	1.60e-01	6.67e-02	0.272	0.113	2.404	0.016
glacier	-5.00e+01	1.33e+01	-0.222	0.059	-3.767	<<0.001
bfi	7.71e-03	1.21e-02	0.175	0.275	0.637	0.524
TAILWATER	-3.60e+00	4.49e-01	-3.599	0.449	-8.014	<<0.001
airtemp	4.74e-01	9.89e-02	0.651	0.136	4.794	<<0.001
flow	-3.89e-02	9.79e-02	-0.068	0.17	-0.398	0.691

* This NorWeST canopy shade data was substituted with new shade data in this study (Section 2.2 Vegetation shading).

Average reach shade percentages varied widely among the three levels of shading (Figure 2). Topographic (no vegetation shading) had an average reach shade of ~9% (Figure 2A), while restored vegetation shading averaged ~85% (Figure 2C). Current vegetation shading averaged across all stream reaches was ~50% (Figure 2B). The difference between current and topographic shading landscapes highlights the higher percent shading in the Cascade Mountains separating the Oregon Coast and Mid-Columbia processing units (Figure 2D). The difference between the current and restored vegetation percent shading predictions highlights areas where restoration is more likely to have benefits for cooling stream temperatures.

Stream temperature predictions for the scenario using current shade and present climate had a simple average (no weighting to the segments) temperature of 14.2°C (Figure 3A) and was ~1°C cooler (Figure 3D) than the average stream temperature in 2040 with current shade (15.3°C) (Figure 3B). Similarly, the average stream temperature predictions in 2080 (16.2°C; Figure 3C) were about 1°C warmer than in 2040 and 2°C warmer than the present climate (Figure 3E).

Stream temperature predictions for the scenario using restored shade and the present climate had a simple average stream temperature of 13.7°C (Figure 4A) and was ~0.5°C cooler (Figure 4D) than the baseline of current shade and the present climate (Figure 3A). The average stream temperature in 2040 with restored shade was 14.7°C (Figure 4B) and 15.7°C in 2080 (Figure 4C). The average difference between the baseline of current vegetation and present climate (Figure 3A) with the predictions for restored vegetation shading in 2080 was 1.5°C (Figure 4E).

When we compare the temperature predictions between the current vegetation shade and topographic shade scenarios, we can see how much worse (warmer) stream temperatures could get if riparian vegetation were removed from the system. For topographic shading (no riparian vegetation), average temperature predictions across the region were 14.8°C for the present climate (Figure 5A), 15.9°C in 2040 (Figure 5B), and 16.8°C in 2080 (Figure 5C). The difference between current vegetation in the present climate and topographic shading temperature predictions in 2040 (difference between Figures 3A and 5B) was 1.7°C and 2.6°C in 2080 (difference between Figures 3A and 5C).

Table 6. Mid-Columbia River SSN model parameter raw (Raw) and standardized (Std.) estimates (Est), standard errors (SE), t-statistics (t), and p-values (p). Parameter abbreviations as in Table 2.

Parameter	Raw Est	Raw SE	Std. Est	Std. SE	t	p
(Intercept)	1.41e+01	2.31e-01	14.08	0.231	61.06	<<0.001
elev	-4.60e-03	3.03e-04	-4.07	0.268	-15.19	<<0.001
canopy*	-1.53e-02	1.78e-03	-0.903	0.105	-8.595	<<0.001
slope	-9.09e+00	1.64e+00	-0.49	0.089	-5.531	<<0.001
precip	-1.34e-03	2.62e-04	-1.334	0.262	-5.094	<<0.001
drainage	5.41e-06	1.89e-06	0.609	0.213	2.855	0.004
lat	-4.77e-06	2.58e-06	-0.774	0.419	-1.849	0.065
water	7.42e-01	7.19e-02	1.581	0.153	10.32	<<0.001
bfi	-6.54e-02	1.77e-02	-1.172	0.317	-3.694	<<0.001
TAILWATER	-6.26e-01	6.31e-01	-0.626	0.631	-0.991	0.322
airtemp	4.30e-01	7.00e-02	0.757	0.123	6.145	<<0.001
flow	-5.57e-02	8.63e-02	-0.091	0.141	-0.646	0.519

* This NorWeST canopy shade data was substituted with new shade data in this study (Section 2.2 Vegetation shading).

To identify which type of streams might benefit most from riparian shade restoration, the difference between current and restored vegetation shading temperature predictions for the present climate were filtered to include only the stream segments that were predicted to cool by 1°C or more (Figure 6A). Stream segments cooling 1°C or more under restored conditions are rather extensive across the study system (Figure 6A). One area within the study system that did not show much temperature cooling when restoring riparian vegetation was the Cascade Mountain region (Figure 6A). A likely cause of this would be that little additional shade was provided when restoring vegetation in this area (Figure 2E). When looking closer at the sites based on their size (as a function of bankfull width – BFW – in meters) most sites are less than 50m wide (Figure 6B) and of the sites that cooled the most under the restored riparian vegetation conditions, sites less than 5m wide cooled most frequently (Figure 6C). While mostly small streams cooled under restored conditions, it should be noted that the cumulative effects of these cooled small segments resulted in a small number of larger systems (up to 20m BFW) also predicted to cool by at least 1°C (Figure 6C).

Shifting the focus from summarizing the entire landscape to just the points where tributaries join the mainstem Columbia River, we can identify how temperatures might shift and create or maintain cold water plumes at these confluences. Flow-weighted average tributary outflow temperatures for all 198 tributaries ranged between ~18.5°C and ~21°C across all nine scenarios (Figure 7 diamonds). Weighting mean temperatures by individual processing units (either Oregon Coast or Mid-Columbia), resulted in a larger range in mean temperature from ~17.75°C to ~21.5°C among all nine scenarios (Figure 7 all triangles). Simple averages (no flow-weighting) for tributary temperature had a cooler range from ~16°C to ~19°C (Figure 7 squares). The flow-weighted mean tributary temperature difference (both Oregon Coast and Mid-Columbia processing units combined) between current and restored shade for the present climate is ~0.4°C. Additionally, the predicted warming between present and 2040 climates for these tributaries with current shade indicates about a 1°C increase in temperature. However, the mean tributary temperature in 2040 for the restored vegetation shading scenario is only ~0.5°C warmer than the present climate and current vegetation shade prediction (comparing means using both processing unit flow weights) (Figure 7).

Individual tributaries to the mainstem Columbia River have different magnitudes of response to restored riparian vegetation at their outflow segments (Figures 8 and 9). Some large tributaries (e.g., Deschutes River and John Day River) appear to be minimally influenced by either adding riparian vegetation or removing it. For example, the predicted stream outflow temperatures for all three shading scenarios of the Deschutes River in the present climate are within 0.1°C of each other. In contrast, some tributaries have large temperature responses at their outflows to restoring riparian shading (e.g., Little White Salmon, Rock Creek, and Skamokawa Creek). For example, the Little White Salmon River has a restored vegetation temperature prediction at its outflow that is >1°C cooler than the current vegetation shading temperature prediction. Furthermore, there are also tributaries that appear more susceptible to riparian vegetation loss than others (e.g., Big Creek in Cathlamet Bay and Elochoman Slough). In these systems, small outflow temperature changes were predicted between current and restored vegetation temperature outflow predictions, but large warming differences were predicted when removing riparian vegetation (topographic shading only predictions) (Figure 8).

We characterized individual tributaries in terms of how influential they were in driving the lower flow-weighted mean tributary outflow temperature in the restored vegetation scenario (Figure 7). Using the absolute temperature difference between current shade and restored shade scenarios for the present climate (Figure 9A) and the mean August flow weights, each tributary’s percent influence can be estimated in terms of how important it is for cooling the flow-weighted mean temperature between these two scenarios (Figure 7). This influence highlights how small absolute temperature differences in some tributaries with large mean August discharges are still overwhelmingly driving the mean temperature of the tributary outflows in this study (Figure 9B). Similarly, the same process can be used to identify the influence of each tributary on the warming predicted when comparing the present climate/current shade to the present climate/topographic shade scenario (Figure 9C).

A couple caveats to these results should be noted. First, the mean August discharge values used in this study are taken from NHDPlus v2 EROM data (McKay et al. 2012) which are averages from 1971 through 2000. This historical discharge average overlaps with the SSN model data for 1993-2000, but a majority of the temperature and covariate data used to fit the models comes from 2001-2011. Though the timeframes of data overlap, they are not perfectly coordinated and are therefore not ideal. However, we do not believe this mismatch influences or bias the results in a significant or systematic way.

Second, the feasibility of restoring riparian shade across the entire study region is rather low. Rapid tree and riparian vegetation planting protocols do exist. These protocols use drones to plant seed pods at a rate of approximately three ha of land per hour from companies like BioCarbon Engineering (www.biocarbonengineering.com). Assuming a 25-meter buffer is restored along each stream bank, a single operator (controlling up to six drones at a time) could initiate the restoration process by planting seed pods along almost 30 kilometers of stream for each 8-hour field day. Scaling this effort up to a full field season (12 weeks or 60 workdays) and this single operator could feasibly plant riparian vegetation along roughly 1,800 km of river. However, the likelihood of land access and financial resources to implement a large-scale restoration effort across the entire study region are low.

Despite these caveats, this study presents two baselines for the best- and worst-case scenarios for riparian vegetation (Restored and Topographic respectively). These bookends help bound the possibilities for using riparian vegetation restoration as a management tool to reduce stream temperatures at both local and regional spatial extents. It is our opinion that riparian vegetation management will be most effective as a stream temperature restoration tool when paired with additional stream temperature management operations.

3 Conclusions

The results of this research offer three main conclusions.

1. Riparian shade restoration is capable of decreasing stream temperatures across the study region.
2. The streams that demonstrate the greatest potential benefit (stream temperature decrease) from riparian shade restoration are streams with bank full widths less than five meters.
3. The flow-weighted, average August stream temperature of tributaries reaching the mainstem of the Columbia River is 0.4°C lower when riparian shade has been restored across the system. The benefit of this temperature decrease from restoration is a reduction in about half the predicted warming for the 2040s.

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5 Figures

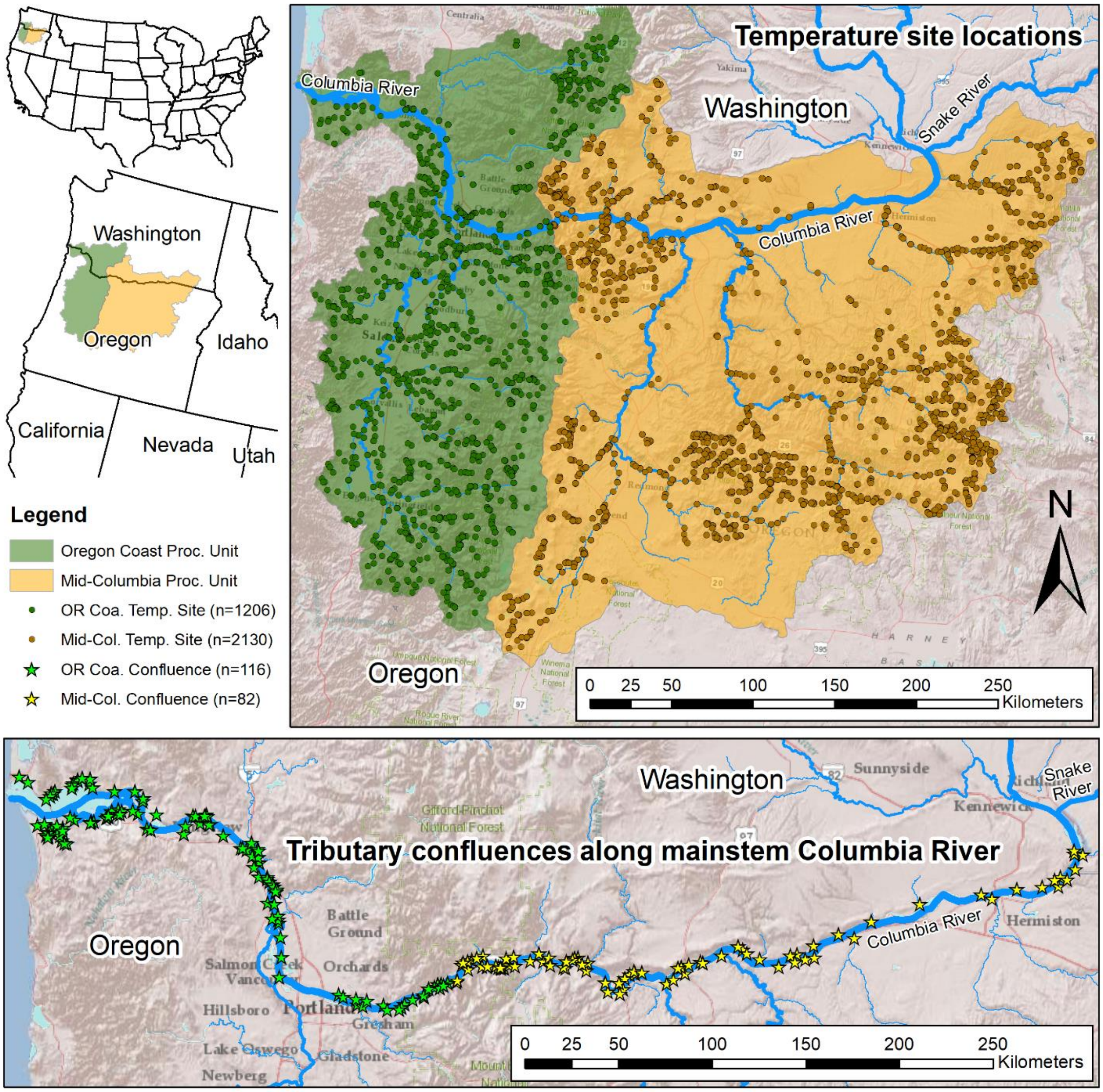

Figure 1. Study region encompassing the Columbia River tributaries downstream of the confluence with the Snake River. Highlighted, for each processing unit region, are the temperature sensor locations for observed temperature data and the locations of the confluences of the tributaries to the mainstem Columbia River.

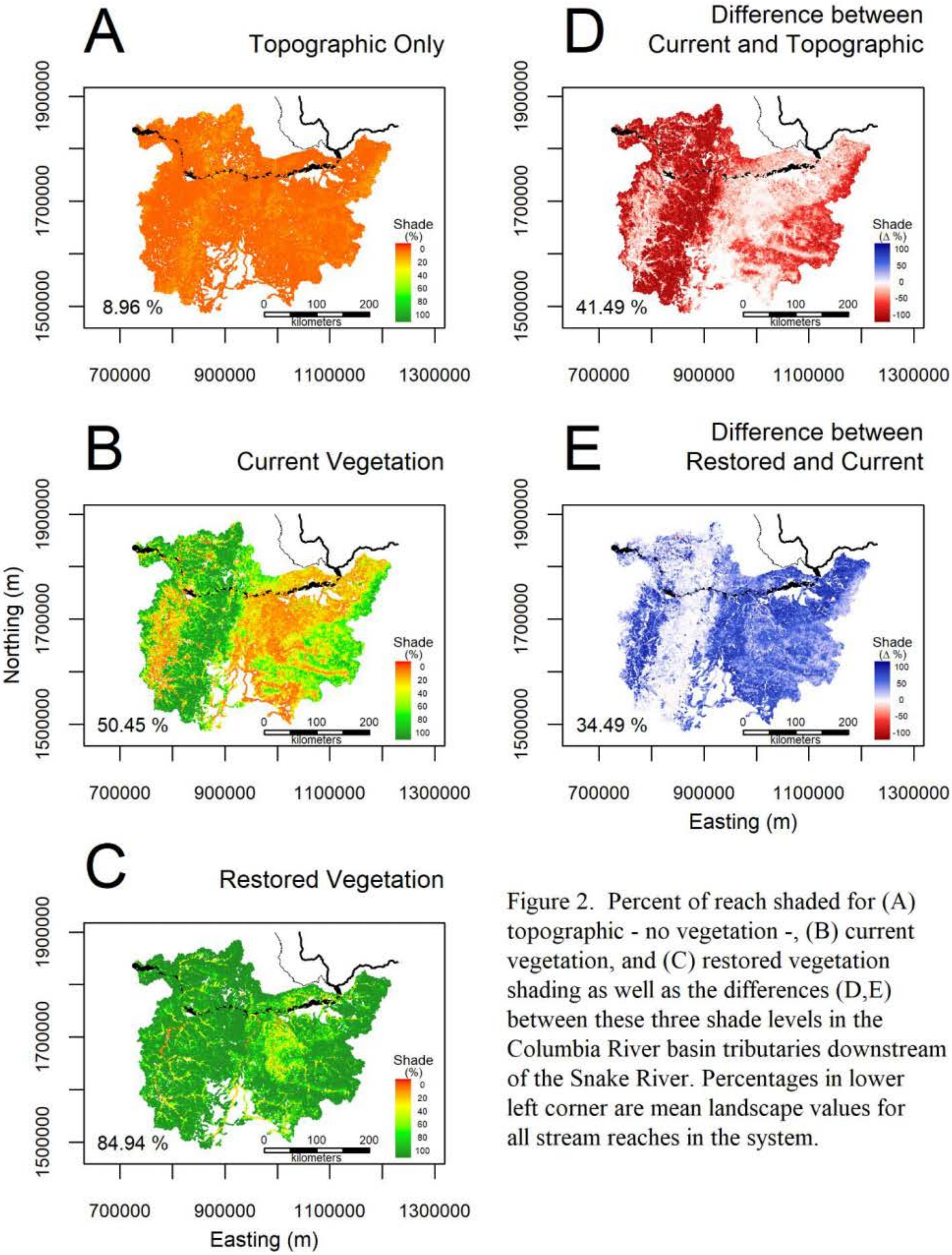

Figure 2. Percent of reach shaded for (A) topographic - no vegetation -, (B) current vegetation, and (C) restored vegetation shading as well as the differences (D,E) between these three shade levels in the Columbia River basin tributaries downstream of the Snake River. Percentages in lower left corner are mean landscape values for all stream reaches in the system.

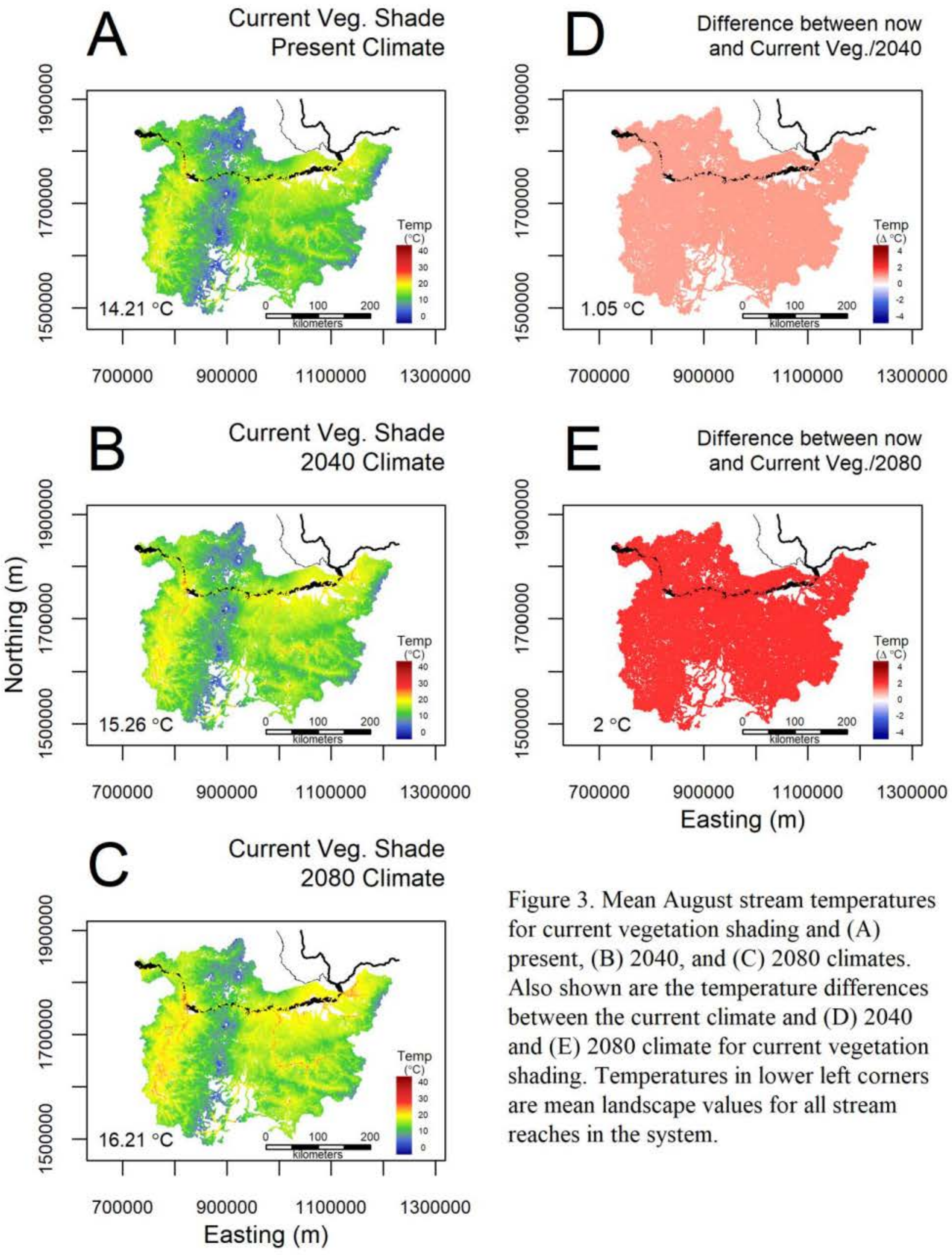

Figure 3. Mean August stream temperatures for current vegetation shading and (A) present, (B) 2040, and (C) 2080 climates. Also shown are the temperature differences between the current climate and (D) 2040 and (E) 2080 climate for current vegetation shading. Temperatures in lower left corners are mean landscape values for all stream reaches in the system.

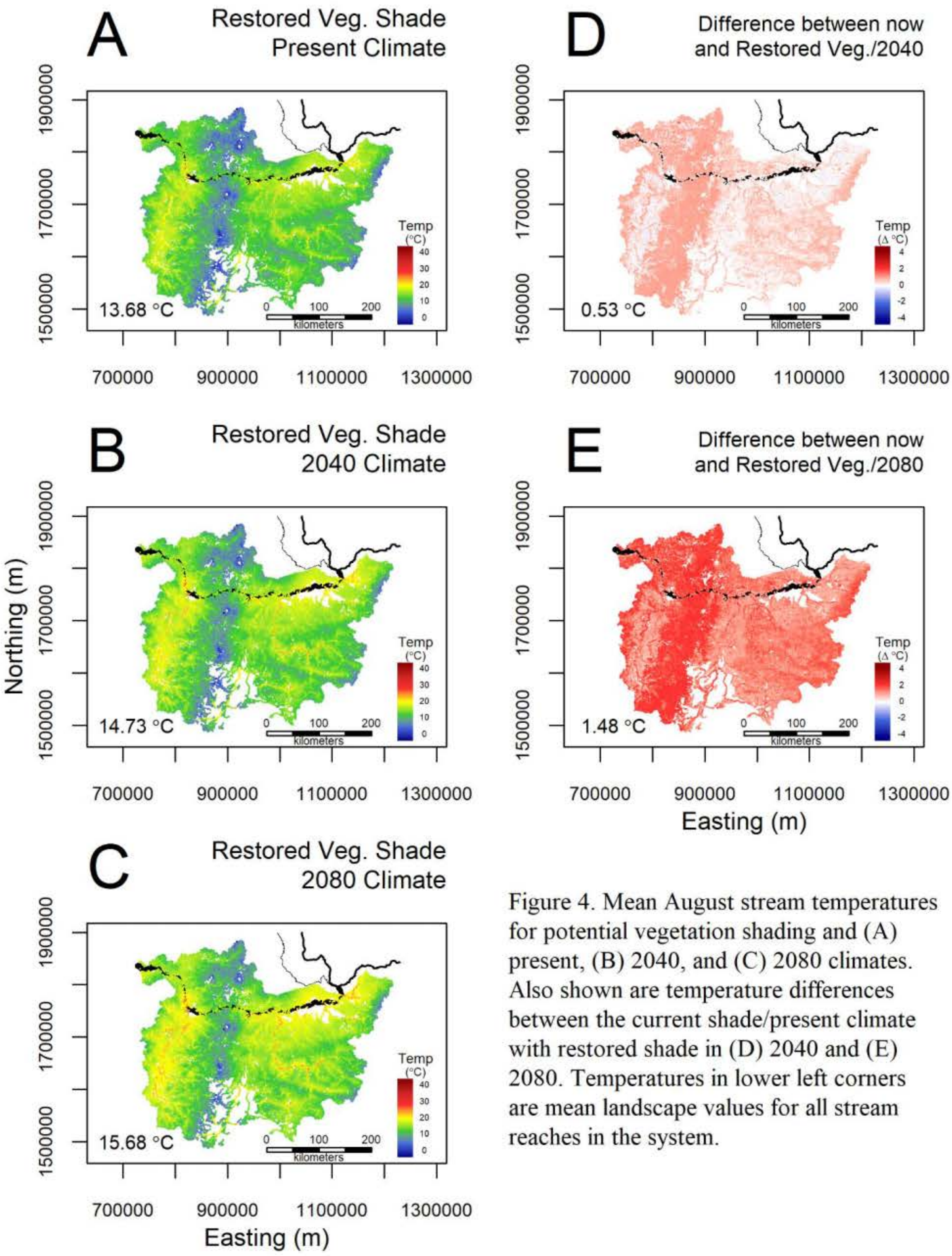

Figure 4. Mean August stream temperatures for potential vegetation shading and (A) present, (B) 2040, and (C) 2080 climates. Also shown are temperature differences between the current shade/present climate with restored shade in (D) 2040 and (E) 2080. Temperatures in lower left corners are mean landscape values for all stream reaches in the system.

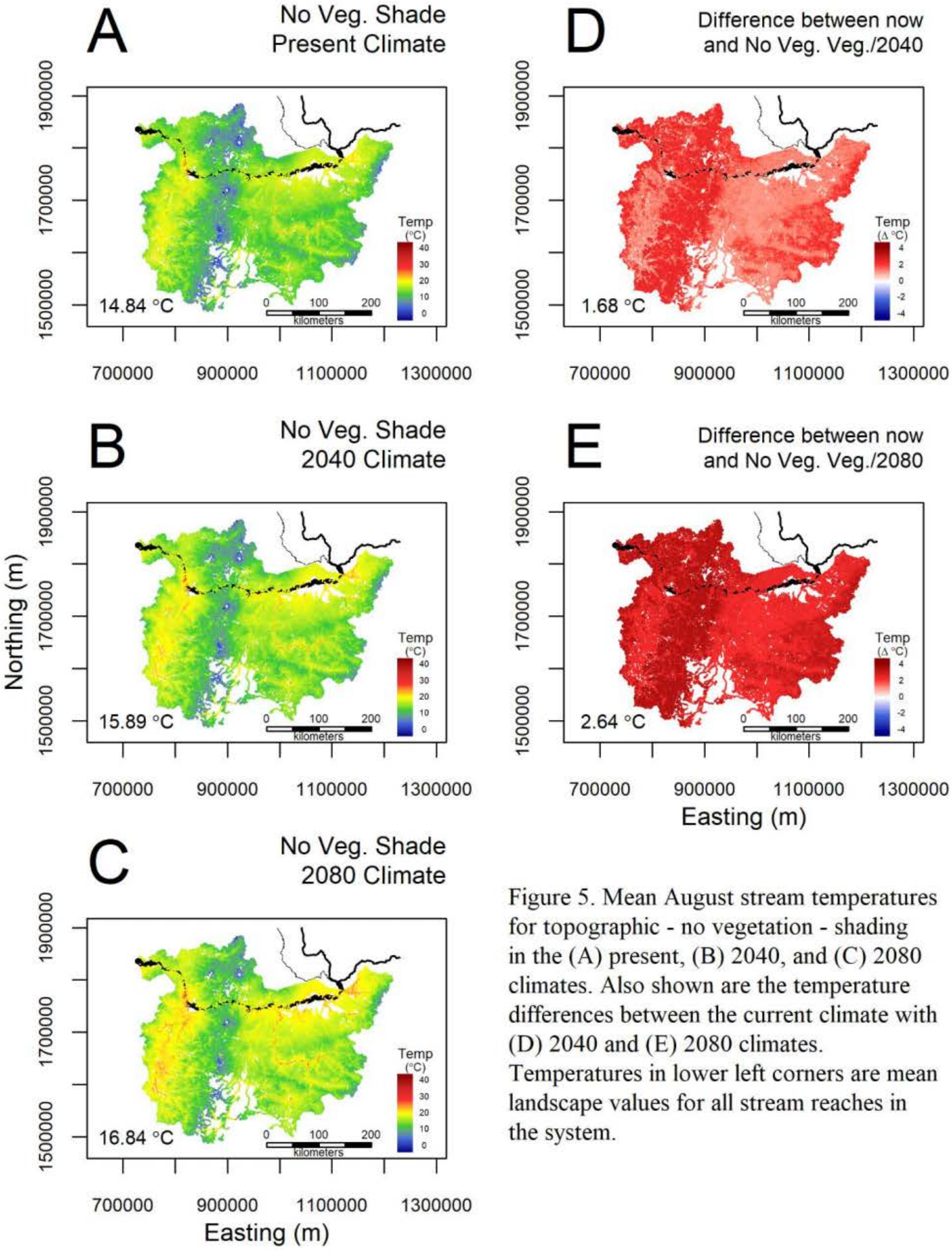

Figure 5. Mean August stream temperatures for topographic - no vegetation - shading in the (A) present, (B) 2040, and (C) 2080 climates. Also shown are the temperature differences between the current climate with (D) 2040 and (E) 2080 climates. Temperatures in lower left corners are mean landscape values for all stream reaches in the system.

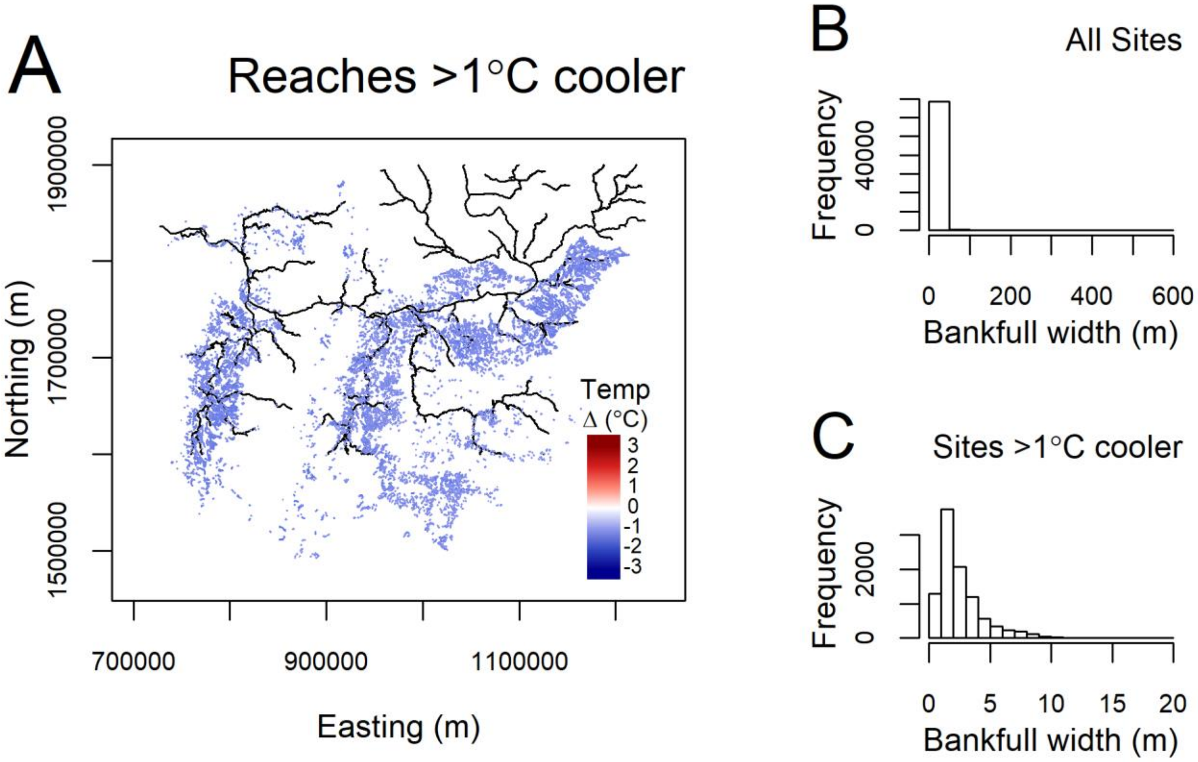

Figure 6. Stream segments with at least a 1°C temperature decrease (A) when comparing current and restored vegetation shade temperatures under the present climate. Histograms present (B) the range in size of streams (using bankfull width – BFW – as a size surrogate) within the study system and (C) highlight that a majority of the reaches that cool when restoring riparian vegetation are <5m BFW.

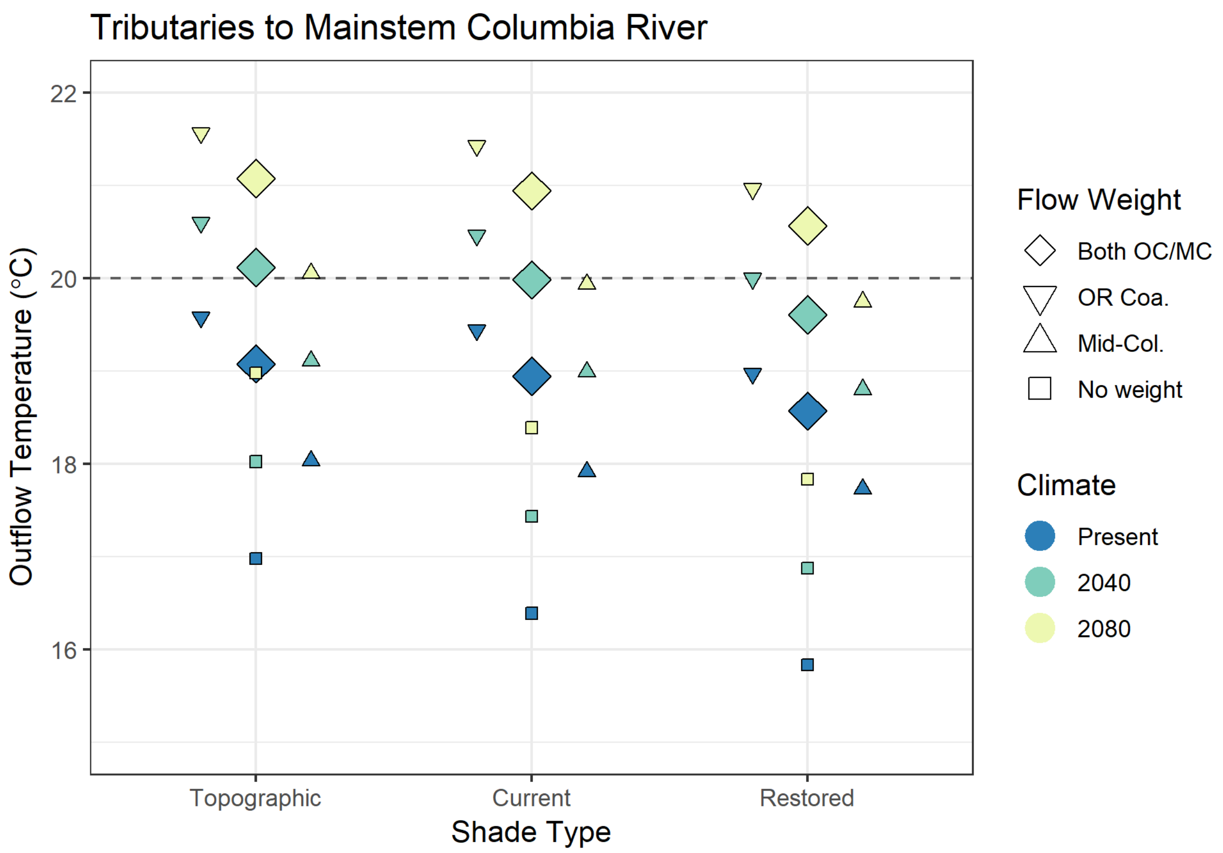

Figure 7. Mean tributary outflow temperatures for nine different scenarios that have been weighted by mean August discharge values (flow-weighted) with difference baseline groupings (Both Oregon Coast and Mid-Columbia processing units together: Both OC/MC (n=198); individual processing unit groups: OR Coa. (n=116) and Mid-Col. (n=82); No weighting – simple arithmetic mean (n=198)).

Figure 8. Tributary outflow temperatures for present climate scenarios. Only tributaries with mean August discharge greater than 0.5 m^3/s shown. Vertical lines indicate the flow-weighted mean temperature for all tributaries (n=198) at each shade level (dotted = topographic, solid = current, dashed = restored). Percentages indicate the relative influence each named tributary has on cooling (left percentages) the flow-weighted mean temperature from Current to Restored Shade (solid to dashed vertical lines) and warming (right percentages) the flow-weighted mean temperature from Current to Topographic Shade (solid to dotted vertical lines).

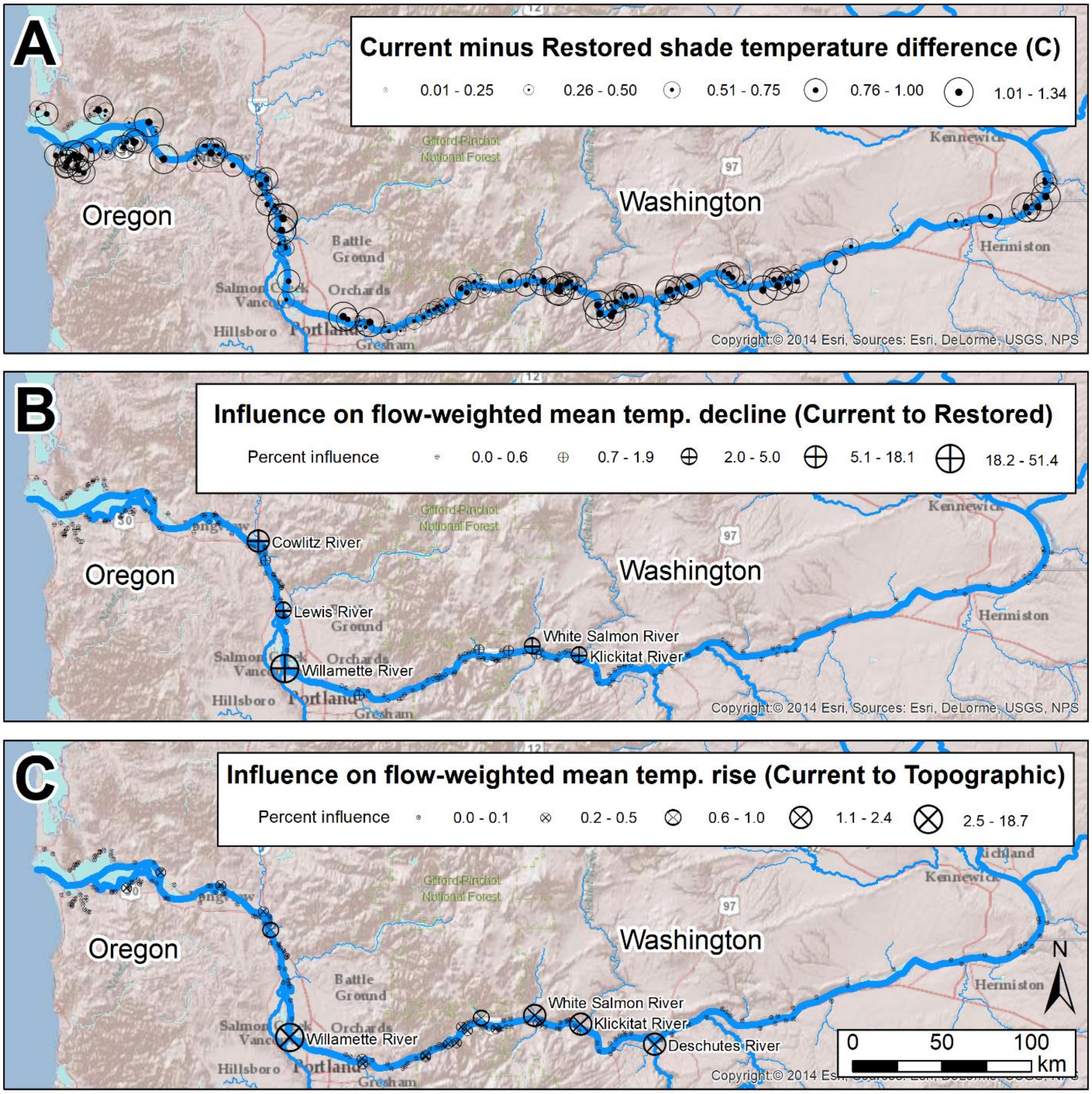

Figure 9. Tributary temperature differences (A) between current and restored shade for the present climate. The percent influence (B) of the tributary on the flow-weighted mean decrease in temperature (see Figure 7) between current and restored shade scenarios – labelled tributary outflows have at least a 3% influence on the mean temperature decline between scenarios. Also, the percent influence on flow-weighted mean temperature rise (C) between the current and topographic shade scenarios – labelled tributaries have at least a 2% influence on temperature rise between scenarios.

6 Appendix

This appendix presents details for each tributary outflow to the mainstem Columbia River in this study. The “Mean August Discharge” values come from the NHDPlus v2 EROM mean monthly flow estimates (McKay et al. 2012). “Restored Temp. Difference” comes from the Restored scenario temperatures at the outflows being subtracted from the Current scenario outflow temperatures for the Present Climate. The “Restored Temp. Influence” is the percent influence the outflow has on the flow-weighted mean temperature difference between the Current Shade and Restored Shade scenarios for the Present Climate (Figure 7). Similarly, the “Topographic Temp. Difference” is the difference between Topographic and Current Shade temperatures for the Present Climate and the “Topographic Temp. Influence” is the percent influence that each tributary has on the temperature rise between the Topographic and Current Shade temperatures for the Present Climate (Figure 7).

Tributary Name	**Lat**	**Long**	**River Mile**	**Mean August Discharge (m^3/s)**	**Discharge Weight**	**Restored Temp. Difference (°C)**	**Restored Temp. Influence**	**Topographic Temp. Difference (°C)**	**Topographic Temp. Influence**
Abernethy Creek	46.189111	-123.168146	51.70	0.2915	0.001198	-0.67	0.08%	0.60	0.07%
Alder Creek	45.838588	-119.928626	254.20	0.1296	0.000533	-0.65	0.03%	0.08	0.00%
Bradbury Slough	46.166059	-123.145733	51.39	0.0192	0.000079	0.00	0.01%	0.21	0.00%
Bridal Veil Creek	45.551194	-122.178912	128.69	0.2099	0.000863	-0.13	0.01%	1.04	0.09%
Burris Creek_Burke Creek	45.945014	-122.778866	76.80	0.0856	0.000352	-0.41	0.01%	0.98	0.03%
Burris Creek_Burris Creek	45.939249	-122.784296	76.80	0.0856	0.000352	-1.34	0.05%	0.06	0.00%
Burris Creek_Canyon Creek	45.954846	-122.792430	76.80	0.0856	0.000352	-0.15	0.01%	1.23	0.04%
Burris Creek_Mill Creek	45.961513	-122.797464	76.80	0.0856	0.000352	-0.41	0.01%	0.98	0.03%
Burris Creek_Unnamed_A	45.936375	-122.782614	76.80	0.0856	0.000352	-1.28	0.04%	0.12	0.00%
Bybee Creek	45.971195	-122.813478	76.06	0.0146	0.00006	0.00	0.00%	1.11	0.00%
Cabin Creek	45.684742	-121.695647	156.09	0.0089	0.000037	0.00	0.00%	1.11	0.00%
Carson Creek	45.716598	-121.820196	150.12	0.0375	0.000154	-0.60	0.01%	0.77	0.01%
Catherine Creek	45.710843	-121.359901	173.55	0.0224	0.000092	0.00	0.01%	0.34	0.00%
Cathlamet Bay_Bear Creek_D	46.169496	-123.667384	20.63	0.2737	0.001125	-0.68	0.08%	0.47	0.05%
Cathlamet Bay_Big Creek_F	46.184031	-123.594445	24.30	0.7720	0.003173	-0.45	0.14%	0.81	0.26%
Cathlamet Bay_Blind Slough_N	46.205727	-123.522361	24.85	0.0501	0.000206	-0.82	0.02%	0.42	0.01%
Cathlamet Bay_Fertile Valley Creek_G	46.186601	-123.585774	24.36	0.0463	0.00019	-0.83	0.02%	0.47	0.01%

Tributary Name	Lat	Long	River Mile	Mean August Discharge (m^3/s)	Discharge Weight	Restored Temp. Difference (°C)	Restored Temp. Influence	Topographic Temp. Difference (°C)	Topographic Temp. Influence
Cathlamet Bay_Gnat Creek_L	46.195951	-123.530535	24.73	0.3069	0.001261	-0.59	0.08%	0.32	0.04%
Cathlamet Bay_Grizzly Slough_J	46.202410	-123.566604	24.61	0.3833	0.001576	-0.57	0.09%	0.81	0.13%
Cathlamet Bay_Hillcrest Creek_E	46.170516	-123.654150	21.06	0.0577	0.000237	-0.22	0.01%	0.74	0.02%
Cathlamet Bay_John Day River_B	46.176475	-123.747900	16.40	0.0757	0.000311	-0.89	0.03%	0.46	0.01%
Cathlamet Bay_Little Creek_F	46.183090	-123.594603	24.30	0.7720	0.003173	-0.33	0.10%	1.06	0.34%
Cathlamet Bay_Marys Creek_C	46.167253	-123.671733	20.51	0.0372	0.000153	-0.42	0.01%	0.74	0.01%
Cathlamet Bay_Mill Creek_A	46.185436	-123.767743	15.53	0.0223	0.000092	0.00	0.00%	1.35	0.00%
Cathlamet Bay_Unnamed_I	46.205664	-123.569271	24.54	0.0029	0.000012	0.00	0.00%	1.34	0.00%
Cathlamet Bay_Unnamed_K	46.197833	-123.543717	24.67	0.0080	0.000033	0.00	0.00%	1.05	0.00%
Cathlamet Bay_Unnamed_M	46.211477	-123.538018	24.79	0.0135	0.000056	0.00	0.00%	0.27	0.00%
Cathlamet Bay_Warren Slough_H	46.190428	-123.585336	24.42	0.0041	0.000017	0.00	0.00%	1.06	0.00%
Chapman Creek	45.724781	-120.316496	233.64	0.0139	0.000057	0.00	0.00%	0.21	0.00%
Chenoweth Creek	45.633926	-121.202882	183.62	0.0325	0.000134	-1.21	0.02%	0.17	0.00%
China Ditch	45.718392	-120.201942	238.23	0.0071	0.000029	0.00	0.00%	0.04	0.00%
Chinook River	46.302394	-123.971467	2.67	0.1371	0.000563	-0.94	0.05%	0.39	0.02%
Clatskanie River_Beaver Slough_A	46.129434	-123.223746	48.28	0.9157	0.003764	-0.70	0.27%	0.24	0.09%
Clatskanie River_Unnamed_B	46.155317	-123.215152	48.28	0.0042	0.000017	0.00	0.00%	0.91	0.00%
Coal Creek Slough_Coal Creek Slough	46.189075	-123.111279	54.00	0.3299	0.001356	-0.51	0.07%	0.79	0.11%
Coal Creek Slough_Fall Creek	46.194109	-123.116957	54.00	0.3299	0.001356	-0.09	0.01%	1.21	0.16%
Coopey Creek	45.562224	-122.165267	129.56	0.0223	0.000092	0.00	0.00%	1.16	0.00%
Cowlitz River_Cowlitz River_B	46.100499	-122.900040	65.80	102.8619	0.422808	-0.43	18.12%	0.01	0.41%
Cowlitz River_Owl Creek Unnamed_C	46.075335	-122.866407	68.04	0.0895	0.000368	-0.87	0.03%	0.52	0.02%
Cowlitz River_Owl Creek_C	46.080462	-122.869231	68.04	0.0895	0.000368	-0.45	0.02%	0.91	0.03%
Cowlitz River_Unnamed_D	46.052668	-122.867636	69.41	0.0003	0.000001	0.00	0.00%	1.31	0.00%
Crooked Creek_Crooked Creek_A	46.295793	-123.676614	20.13	0.1756	0.000722	-0.43	0.03%	0.94	0.07%
Crooked Creek_Hitchcock Creek_B	46.283705	-123.661061	20.26	0.0170	0.00007	0.00	0.00%	1.37	0.00%
Deep River	46.315247	-123.710835	19.08	0.2021	0.000831	-1.18	0.10%	0.17	0.01%
Deschutes River	45.630026	-120.910445	200.83	126.7829	0.521134	-0.01	0.64%	0.05	2.39%

Tributary Name	**Lat**	**Long**	**River Mile**	**Mean August Discharge (m^3/s)**	**Discharge Weight**	**Restored Temp. Difference (°C)**	**Restored Temp. Influence**	**Topographic Temp. Difference (°C)**	**Topographic Temp. Influence**
Dog Creek	45.714815	-121.678281	157.52	0.0687	0.000282	-0.09	0.00%	1.05	0.03%
Driscoll Slough	46.147058	-123.399808	39.83	0.0355	0.000146	-0.31	0.00%	1.08	0.02%
Duncan Creek	45.613133	-122.050831	136.76	0.1436	0.00059	-0.63	0.04%	0.58	0.03%
Eagle Creek	45.635682	-121.917390	142.73	2.0360	0.008369	-0.44	0.37%	0.56	0.47%
Eightmile Creek	45.660763	-121.086600	192.13	0.0085	0.000035	0.00	0.00%	0.27	0.00%
Ellison Slough	46.247550	-123.418603	33.24	0.0126	0.000052	0.00	0.00%	1.34	0.00%
Elochoman Slough	46.239011	-123.420932	33.31	0.7923	0.003257	-0.46	0.15%	0.63	0.20%
Fifteenmile Creek	45.611468	-121.118793	188.90	1.0338	0.00425	-0.89	0.38%	0.11	0.05%
Fivemile Creek	45.647694	-121.111181	190.70	0.0085	0.000035	0.00	0.00%	0.19	0.00%
Flume Creek	46.161643	-123.103018	55.30	0.0126	0.000052	0.00	0.00%	0.85	0.00%
Fox Creek	46.082298	-122.940805	65.06	0.0271	0.000111	0.00	0.00%	1.06	0.00%
Frank Born Creek	46.293910	-123.758268	16.71	0.0101	0.000042	0.00	0.00%	1.30	0.00%
Gee Creek	45.843706	-122.771451	84.57	0.0761	0.000313	-0.49	0.02%	0.79	0.02%
Germany Creek	46.190421	-123.124738	53.62	0.2395	0.000985	-0.58	0.06%	0.58	0.06%
Glade Creek	45.896738	-119.696374	267.62	0.1073	0.000441	-0.43	0.02%	0.16	0.01%
Goble Creek	46.020027	-122.888370	71.15	0.0932	0.000383	-0.32	0.01%	1.06	0.04%
Gorton Creek	45.688284	-121.772379	152.05	0.2135	0.000878	-0.60	0.05%	0.74	0.06%
Grays Creek	45.687981	-121.795154	151.61	0.0505	0.000208	-0.03	0.00%	1.29	0.03%
Grays River	46.312667	-123.673249	19.64	1.8063	0.007425	-0.56	0.41%	0.19	0.14%
Green Creek	46.163287	-123.096949	55.61	0.0554	0.000228	-0.25	0.01%	1.11	0.03%
Harphan Creek	45.688673	-121.767896	152.92	0.0492	0.000202	-0.28	0.01%	1.07	0.02%
Herman Creek	45.678819	-121.860883	147.45	1.2881	0.005295	-0.83	0.44%	0.46	0.24%
Hood River	45.705518	-121.502481	165.66	10.5919	0.043537	-0.43	1.89%	0.06	0.25%
Horsetail Creek	45.591813	-122.073866	134.59	0.8280	0.003403	-0.66	0.22%	0.59	0.20%
Jewett Creek	45.717609	-121.474351	166.84	0.0202	0.000083	0.00	0.01%	0.18	0.00%
Jim Crow Creek	46.271455	-123.555457	26.16	0.1215	0.000499	-0.26	0.01%	1.01	0.05%
John Day River	45.725281	-120.646590	215.49	6.9430	0.028539	-0.09	0.25%	0.01	0.02%
Kalama River	46.034806	-122.862570	70.53	7.4765	0.030732	-0.35	1.09%	0.26	0.80%

Tributary Name	**Lat**	**Long**	**River Mile**	**Mean August Discharge (m^3/s)**	**Discharge Weight**	**Restored Temp. Difference (ºC)**	**Restored Temp. Influence**	**Topographic Temp. Difference (ºC)**	**Topographic Temp. Influence**
Kanaka Creek	45.701558	-121.884883	147.39	0.0315	0.00013	-0.28	0.00%	1.09	0.01%
Klickitat River	45.700720	-121.286712	176.84	24.1321	0.099194	-0.42	4.15%	0.24	2.38%
Lake River	45.834861	-122.768466	84.94	0.7216	0.002966	-0.59	0.17%	0.14	0.04%
Latourell Creek	45.542023	-122.249351	124.96	0.0915	0.000376	-0.53	0.02%	0.72	0.03%
Lawton Creek	45.558422	-122.268231	124.77	0.0519	0.000213	-0.47	0.01%	0.81	0.02%
Lewis River	45.857361	-122.773259	84.32	40.1253	0.164933	-0.30	4.99%	0.00	0.00%
Lindsey Creek	45.686361	-121.717456	155.34	0.3150	0.001295	-0.10	0.01%	1.25	0.16%
Little White Salmon River	45.719813	-121.642675	158.70	2.4892	0.010232	-0.89	0.91%	0.12	0.13%
Major Creek	45.716929	-121.351368	173.86	0.1252	0.000515	-0.53	0.03%	0.39	0.02%
McBride Creek	45.900934	-122.822812	80.03	0.0165	0.000068	0.00	0.00%	1.11	0.00%
McCord Creek	45.616902	-121.997038	138.88	0.4159	0.00171	-0.47	0.08%	0.81	0.14%
Mill Creek	46.190683	-123.180790	51.33	0.2930	0.001204	-0.59	0.07%	0.64	0.08%
Moffett Creek	45.624194	-121.978440	139.81	0.2539	0.001044	-0.40	0.04%	0.91	0.10%
Mosier Creek	45.683341	-121.393970	171.44	0.0558	0.000229	-1.05	0.02%	0.21	0.00%
Multnomah Channel	45.848550	-122.799982	83.57	0.8495	0.003492	-0.64	0.22%	0.05	0.02%
Nelson Creek	45.705288	-121.863755	148.13	0.0490	0.000201	-0.24	0.00%	0.98	0.02%
Nice Creek	46.083351	-122.951518	64.81	0.0089	0.000037	0.00	0.00%	1.26	0.00%
Oneonta Creek	45.585538	-122.073189	134.59	0.8280	0.003403	-0.20	0.07%	0.69	0.23%
Owl Creek	46.077945	-122.923212	65.99	0.0054	0.000022	0.00	0.00%	1.33	0.00%
Perham Creek	45.690452	-121.637905	159.13	0.0108	0.000044	0.00	0.00%	1.14	0.00%
Phelps Creek	45.706831	-121.562788	163.05	0.0341	0.00014	-0.82	0.01%	0.57	0.01%
Pine Creek	45.795694	-120.087412	246.13	0.0602	0.000248	-0.16	0.00%	0.11	0.00%
Rock Creek_A	45.692636	-121.891568	146.58	1.3428	0.005519	-0.93	0.51%	0.31	0.17%
Rock Creek_B	45.685602	-121.404868	171.06	0.0597	0.000245	-1.04	0.03%	0.31	0.01%
Rock Creek_C	45.712748	-120.464552	226.18	0.2467	0.001014	-0.54	0.06%	0.00	0.00%
Ruckel Creek	45.641807	-121.912887	143.35	0.1384	0.000569	-0.04	0.00%	1.14	0.07%
Sandy River	45.560793	-122.393467	117.13	13.2864	0.054613	-0.26	1.42%	0.09	0.50%
Schoolhouse Creek_Schoolhouse Creek	45.980907	-122.823386	75.12	0.0455	0.000187	-0.55	0.01%	0.83	0.02%

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Schoolhouse Creek_Unnamed	45.986082	-122.822972	75.12	0.0455	0.000187	-0.46	0.01%	0.91	0.02%
Sisson Creek_Sisson Creek	46.310175	-123.732225	18.21	0.0969	0.000398	-0.31	0.01%	1.02	0.04%
Sisson Creek_Unnamed	46.307350	-123.732065	18.21	0.0969	0.000398	-0.05	0.00%	1.32	0.05%
Skamokawa Creek	46.271926	-123.457242	30.94	0.6429	0.002643	-1.02	0.27%	0.12	0.03%
Skipanon River	46.158412	-123.926192	8.33	0.1276	0.000524	-0.99	0.05%	0.24	0.01%
Starvation Creek	45.683441	-121.687978	156.46	0.0244	0.0001	0.00	0.00%	1.03	0.00%
Summit Creek	45.689977	-121.729536	154.54	0.0274	0.000113	0.00	0.00%	1.25	0.00%
Tanner Creek	45.632388	-121.959582	140.86	1.0681	0.004391	-0.53	0.23%	0.44	0.19%
Threemile Creek_A	45.596359	-121.134989	187.53	0.0205	0.000084	0.00	0.01%	0.26	0.00%
Threemile Creek_B	45.632523	-121.137722	189.21	0.0072	0.00003	0.00	0.00%	0.52	0.00%
Tide Creek	45.987329	-122.863769	73.20	0.1736	0.000713	-0.94	0.07%	0.12	0.01%
Umatilla River	45.914735	-119.350838	284.65	0.5255	0.00216	-0.49	0.11%	0.01	0.00%
Unnamed Trib - 16_Hunt Creek_B	46.197848	-123.443841	34.92	0.0855	0.000352	-0.21	0.01%	0.57	0.02%
Unnamed Trib - 16_Kelly Creek_A	46.206827	-123.467632	32.93	0.0136	0.000056	0.00	0.00%	1.29	0.00%
Unnamed Trib - 17	46.194002	-123.354251	34.49	0.0090	0.000037	0.00	0.00%	1.35	0.00%
Unnamed Trib - 19	46.124607	-123.035238	57.60	0.0214	0.000088	0.00	0.01%	0.52	0.00%
Unnamed Trib - 2	46.245619	-123.884256	9.57	0.0095	0.000039	0.00	0.00%	1.26	0.00%
Unnamed Trib - 21	46.056919	-122.895408	68.10	0.0255	0.000105	0.00	0.01%	0.33	0.00%
Unnamed Trib - 24	45.896680	-122.789947	81.34	0.0191	0.000079	0.00	0.01%	0.14	0.00%
Unnamed Trib - 25	45.785051	-122.760452	89.42	0.0076	0.000031	0.00	0.00%	1.12	0.00%
Unnamed Trib - 28	45.719486	-122.755990	93.39	0.0104	0.000043	0.00	0.00%	0.36	0.00%
Unnamed Trib - 3	46.254442	-123.864597	10.69	0.0127	0.000052	0.00	0.00%	1.17	0.00%
Unnamed Trib - 33	45.593709	-122.481801	112.53	0.0338	0.000139	-1.28	0.02%	0.06	0.00%
Unnamed Trib - 34	45.585812	-122.459411	114.15	0.0075	0.000031	0.00	0.00%	0.55	0.00%
Unnamed Trib - 35A	45.555710	-122.367150	119.61	0.0033	0.000014	0.00	0.00%	0.86	0.00%
Unnamed Trib - 35C	45.573507	-122.346736	119.92	0.0901	0.00037	-1.14	0.04%	0.16	0.01%
Unnamed Trib - 36	45.709232	-121.843122	149.13	0.0209	0.000086	0.00	0.00%	1.15	0.00%
Unnamed Trib - 37	45.684724	-121.706001	155.72	0.0041	0.000017	0.00	0.00%	1.10	0.00%

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Unnamed Trib - 38	45.692550	-121.467194	168.33	0.0043	0.000018	0.00	0.00%	1.25	0.00%
Unnamed Trib - 39	45.705553	-121.390736	172.24	0.0074	0.00003	0.00	0.00%	0.40	0.00%
Unnamed Trib - 4	46.264059	-123.860245	11.37	0.0161	0.000066	0.00	0.00%	1.21	0.00%
Unnamed Trib - 40A	45.717407	-121.333966	174.29	0.0046	0.000019	0.00	0.00%	0.71	0.00%
Unnamed Trib - 40B_Rowena Creek	45.695312	-121.315931	175.54	0.0174	0.000071	0.00	0.01%	0.57	0.00%
Unnamed Trib - 41	45.675041	-121.294724	177.84	0.0023	0.00001	0.00	0.00%	1.17	0.00%
Unnamed Trib - 41B - Mill Creek	45.603222	-121.192029	185.60	0.3283	0.001349	-1.31	0.18%	0.06	0.01%
Unnamed Trib - 42	45.671845	-121.066080	192.81	0.0021	0.000008	0.00	0.00%	0.27	0.00%
Unnamed Trib - 43	45.663585	-121.060112	193.18	0.0009	0.000003	0.00	0.00%	0.23	0.00%
Unnamed Trib - 44	45.667724	-121.028788	194.49	0.0023	0.000009	0.00	0.00%	0.19	0.00%
Unnamed Trib - 46	45.643676	-120.877231	202.50	0.0285	0.000117	-0.59	0.01%	0.17	0.00%
Unnamed Trib - 5	46.263903	-123.850019	11.62	0.0148	0.000061	0.00	0.00%	1.09	0.00%
Unnamed Trib - 50	45.682876	-120.855494	204.74	0.0010	0.000004	0.00	0.00%	0.25	0.00%
Unnamed Trib - 51	45.685672	-120.839425	205.49	0.0007	0.000003	0.00	0.00%	0.23	0.00%
Unnamed Trib - 52	45.665356	-120.822505	205.67	0.0446	0.000183	-0.58	0.01%	0.09	0.00%
Unnamed Trib - 53	45.693912	-120.803615	207.48	0.0039	0.000016	0.00	0.00%	0.12	0.00%
Unnamed Trib - 55	45.704468	-120.748468	210.15	0.0016	0.000007	0.00	0.00%	0.38	0.00%
Unnamed Trib - 56	45.699278	-120.735993	210.52	0.0101	0.000041	0.00	0.00%	0.11	0.00%
Unnamed Trib - 56B	45.754496	-120.567004	219.90	0.0000	0	0.00	0.00%	0.10	0.00%
Unnamed Trib - 57	45.744553	-120.545615	220.46	0.0017	0.000007	0.00	0.00%	0.34	0.00%
Unnamed Trib - 58	45.731802	-120.526493	221.46	0.0026	0.000011	0.00	0.00%	0.27	0.00%
Unnamed Trib - 6	46.271123	-123.841615	11.87	0.0472	0.000194	-0.01	0.00%	1.32	0.03%
Unnamed Trib - 64	45.686803	-120.372914	230.22	0.0049	0.00002	0.00	0.00%	0.01	0.00%
Unnamed Trib - 67	45.702000	-120.296019	233.70	0.0035	0.000015	0.00	0.00%	0.11	0.00%
Unnamed Trib - 68	45.729305	-120.284848	235.00	0.0123	0.000051	0.00	0.00%	0.12	0.00%
Unnamed Trib - 69	45.712213	-120.245450	236.74	0.0040	0.000017	0.00	0.00%	0.05	0.00%
Unnamed Trib - 7	46.281921	-123.760720	16.28	0.0167	0.000069	0.00	0.00%	1.24	0.00%
Unnamed Trib - 76	45.928686	-119.402793	282.35	0.0217	0.000089	0.00	0.01%	0.31	0.00%

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Unnamed Trib - 78	45.946453	-119.230843	290.49	0.0009	0.000004	0.00	0.00%	0.45	0.00%
Unnamed Trib - 8	46.297066	-123.751883	16.90	0.0091	0.000037	0.00	0.00%	1.32	0.00%
Unnamed Trib - 82	45.952824	-119.110770	296.95	0.0191	0.000079	0.00	0.00%	0.23	0.00%
Unnamed Trib - 83	45.977084	-119.050862	300.43	0.0009	0.000004	0.00	0.00%	0.18	0.00%
Unnamed Trib - 84	45.955541	-119.033500	300.74	0.0624	0.000257	-0.66	0.02%	0.21	0.01%
Unnamed Trib - 85	45.986314	-119.023841	302.42	0.0013	0.000005	0.00	0.00%	0.13	0.00%
Unnamed Trib - 86	45.977454	-118.990702	303.23	0.0037	0.000015	0.00	0.00%	0.04	0.00%
Unnamed Trib - 87	46.013155	-118.952064	306.21	0.0056	0.000023	0.00	0.00%	0.06	0.00%
Unnamed Trib - 88	46.063804	-118.955152	309.44	0.0010	0.000004	0.00	0.00%	0.47	0.00%
Unnamed Trib - 89	46.074306	-118.958051	310.50	0.0058	0.000024	0.00	0.00%	0.23	0.00%
Viento Creek	45.693043	-121.665687	157.21	0.0456	0.000188	-0.04	0.00%	1.13	0.02%
Wahkeena Creek	45.577822	-122.125217	131.85	0.4312	0.001772	-0.66	0.12%	0.63	0.11%
Walla Walla River	46.060690	-118.916369	309.38	0.6703	0.002755	-0.26	0.07%	0.07	0.02%
Wallacut River	46.318968	-124.013714	0.99	0.0631	0.000259	-0.73	0.02%	0.63	0.02%
Warren Creek	45.681181	-121.701838	155.78	0.1113	0.000458	-0.04	0.00%	1.03	0.05%
Washougal River	45.579163	-122.398497	117.63	3.8637	0.015882	-0.40	0.64%	0.10	0.15%
Westport Slough	46.143815	-123.382838	40.51	0.2870	0.00118	-1.18	0.14%	0.12	0.01%
White Salmon River	45.732191	-121.521452	164.91	19.6067	0.080592	-0.51	4.08%	0.30	2.41%
Willamette River	45.652661	-122.765913	98.18	243.2826	1	-0.51	51.37%	0.19	18.68%
Willow Creek	45.783518	-120.010406	249.36	0.4153	0.001707	-0.78	0.13%	0.03	0.01%
Wind River	45.722840	-121.790997	151.12	8.3047	0.034136	-0.47	1.61%	0.29	0.99%
Wood Creek	45.758499	-120.205914	239.97	0.0516	0.000212	-0.35	0.01%	0.10	0.00%
Woodward Creek_Hamilton Creek_C	45.629326	-121.991144	139.25	0.6682	0.002747	-0.44	0.12%	0.53	0.14%
Woodward Creek_Hardy Creek_B	45.628946	-122.007190	138.01	0.0902	0.000371	-0.53	0.02%	0.82	0.03%
Woodward Creek_Woodward Creek_A	45.618710	-122.022261	137.70	0.2847	0.00117	-0.52	0.06%	0.61	0.07%
Young Creek	45.543669	-122.191952	127.94	0.0435	0.000179	-0.26	0.00%	1.05	0.02%
Youngs Bay_Adair Slough_A	46.162784	-123.892176	8.82	0.0139	0.000057	0.00	0.00%	0.57	0.00%
Youngs Bay_Cook Slough_H	46.157510	-123.831858	9.88	0.0079	0.000032	0.00	0.00%	0.27	0.00%

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Youngs Bay_Lewis and Clark River_B	46.144994	-123.856725	9.82	0.0142	0.000058	0.00	0.00%	0.60	0.00%
Youngs Bay_Lewis and Clark River_C	46.136756	-123.864909	9.82	0.0207	0.000085	0.00	0.01%	0.43	0.00%
Youngs Bay_Lewis and Clark River_D	46.133314	-123.873312	9.82	0.0038	0.000016	0.00	0.00%	0.64	0.00%
Youngs Bay_Lewis and Clark River_E	46.125811	-123.883309	9.82	0.0093	0.000038	0.00	0.00%	1.30	0.00%
Youngs Bay_Lewis and Clark River_F	46.121003	-123.872479	9.82	0.0024	0.00001	0.00	0.00%	0.37	0.00%
Youngs Bay_Lewis and Clark River_G	46.118343	-123.874799	9.82	1.0190	0.004189	-0.83	0.35%	0.12	0.05%
Youngs Bay_Youngs River_I	46.150696	-123.803364	10.00	0.1785	0.000734	-1.28	0.09%	0.04	0.00%
Youngs Bay_Youngs River_J	46.140460	-123.824361	10.00	0.0044	0.000018	0.00	0.00%	0.87	0.00%
Youngs Bay_Youngs River_K	46.140277	-123.804128	10.00	0.0053	0.000022	0.00	0.00%	1.24	0.00%
Youngs Bay_Youngs River_L	46.123704	-123.818614	10.00	0.0134	0.000055	0.00	0.01%	0.36	0.00%
Youngs Bay_Youngs River_M	46.107312	-123.809844	10.00	0.0457	0.000188	-0.92	0.02%	0.28	0.01%
Youngs Bay_Youngs River_N	46.098987	-123.795353	10.00	0.0070	0.000029	0.00	0.00%	1.10	0.00%
Youngs Bay_Youngs River_O	46.098376	-123.785103	10.00	1.6520	0.006791	-0.79	0.54%	0.06	0.04%