**Incorporating Spatial Heterogeneity in Temperature into Climate Vulnerability Assessments for Coastal Pacific Streams**

**Interim Progress Report** to the North Pacific Landscape Conservation Cooperative
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## Purpose and Objectives

Natural resource managers throughout the North Pacific Landscape Conservation Cooperative (NPLCC) are tasked with complex conservation decisions that address a myriad of existing stressors to rare species (e.g., habitat loss, fragmentation, nonindigenous species). Water temperature, a key driver of ecological processes in aquatic environments, is expected to warm throughout the region as a result of climate change, further stressing stream biota. In addition to consideration of the extent to which water temperature will increase as a result of climate change, successful adaptation strategies for freshwater biota will also consider how *spatial patterns* in water temperature (e.g., locations and spacing of cold water patches) may respond.

Using remotely sensed spatially continuous maximum water temperature data for rivers throughout the lower portion of the NPLCC (Figure 1), our objectives were to:

(1) Characterize distribution of cold water patches, identify potential hydroclimatic and landscape drivers, and evaluate how detection of cold water patches depends on the spatial resolution of water temperature data;

(2) Compare existing and future patterns of thermal heterogeneity to assess the potential influence of climate change; and

(3) Illustrate potential vulnerability of salmon to changes in thermal heterogeneity in two case study watersheds.

Products can be used to identify locations where stream temperature patterns may be most responsive to climate change and will enable conservation planners to choose conservation strategies that will promote future thermal diversity.

## Progress to Date

### *Objective 1: Thermal heterogeneity, potential drivers, and spatial resolution*

Thermal Heterogeneity

We classified remotely sensed water temperature in anadromous portions of NPLCC rivers (data described in Fullerton et al. 2015) into *cool* (<15 °C), *tolerable* (15-20 °C), and *warm* (>20 °C) habitat. These zones correspond to EPA criteria for 7-day average of daily maxima. We then evaluated the density, length, and spacing of *cool* patches within rivers. We also quantified 'peaks' and 'valleys' from a 10-km moving average trend line on longitudinal profiles (i.e., water temperature vs. distance upstream).

Overall, cool water patches were densely distributed within warmer riverine habitat. It is important to keep in mind that the dataset omits smaller tributaries and is therefore more representative of mid to large order rivers. Cool patches were around 200 m long and about 250 m apart, on median; however, considerable among-river variability existed (Figure 2 left panels; Table 1). The density of 'valleys' was lower than the density of 'peaks', but the length and spacing of 'valleys' exceeded the length and spacing of 'peaks' (Figure 2, right panels). The total amount of 'cool' habitat increased when we raised the threshold to 17 °C; however, thermal heterogeneity metrics were similar (Figure 3; Table 1). When cool patches were classified as habitat <12 °C, the total amount decreased, patch density increased, patch length remained similar, and patch spacing increased. Again, variability among rivers was high.

Potential Drivers

We have not made significant progress on identification of drivers of cold water patches. In a related paper, we evaluated relationships between whole-river patterns in water temperature and hydroclimatic drivers (Fullerton et al. 2015). However, within-river relationships are more complex than we initially expected due to the fact that upstream processes influence water temperature downstream. We initiated collaboration with Dan Miller, one of the creators of NetMap (netmaptools.org) and with EPA personnel and expect to make progress on this objective during the next year. We have identified locations along profiles where water temperature decreased in a downstream direction (Figure 4). We will use a GIS to overlay a suite of variables that we believe may be associated with cooling, using data and tools in NetMap.

Spatial Resolution

We binned water temperature data at increasingly coarse resolutions, and found strong nonlinear responses in heterogeneity metrics (Figure 5). Patch density decreased whereas patch length and spacing increased. This finding suggests that there may be substantial thermal heterogeneity at scales below 1-km that may be important for fish.

We compared spatial patterns in water temperature produced from airborne thermal infrared (TIR) surveys with predicted water temperature from NorWeST (Isaak et al

2013). Longitudinal profiles (water temperature vs. distance upstream) were remarkably similar (Figure 6). The TIR data exhibited higher spatial variance; however some of this variance may be due to the fact that TIR data measured summer maxima and NorWeST data represented August means.

### *Objective 2: Future Thermal Heterogeneity*

We evaluated how thermal heterogeneity might change in the future using multiple approaches to forecast water temperature. We then characterized future patch density, size, and spacing and compared distributions to historical patterns. For all rivers in the NPLCC for which we had TIR data, we used one simple and one statistical approach for predicting future water temperatures, described in this section. We are also working on a process-based approach for predicting future water temperature in several case study basins (see next section).

#### Simple Approach

We represented future water temperature as a warmer version of existing temperature (i.e., shifting an entire TIR longitudinal profile up but retaining its original shape). To do this, we increased water temperature everywhere by a constant amount (0.5 to 3 °C). This approach is supported by the temporal consistency of spatial patterns for surveys that were conducted in both cool and warm years (see Figure 1 in Fullerton et al. 2015).

#### Statistical Approach

We expect that relationships between water temperature and climate drivers will differ over space. Therefore, we also projected future water temperature as follows. We used random forest regression to construct relationships between water temperature (from TIR) and three climate covariates suspected to be both highly influential to water temperature and responsive to climate change: (1) mean weekly air temperature between 16 July and 31 August, (2) mean annual precipitation, and (3) the probability that precipitation will fall as snow during winter (Dec, Jan, Feb). Covariate data sources and climate scenarios are described below. We also included distance upstream (km) as a covariate.

Fitted values for these models represented the portion of longitudinal trends that were explained by the 3 climate covariates. Residuals were assumed to be patchiness in longitudinal profiles controlled by processes not included in models, such as local groundwater inputs, anomalies in adjacent landscape features, network geometry or stream geomorphology. We predicted future longitudinal trends by substituting future values of the 3 climate covariates. Finally, we summed future trends and residuals from the fitted model to get potential future longitudinal profiles.

#### Climate Scenarios

We considered covariate data from historical (1950-2005) and future periods (2006-2100), where future values are representative of expectations under a greenhouse gas concentration scenario that is currently considered to be most realistic: representative concentration pathway (RCP) 8.5, a high emissions scenario (Taylor et al. 2012). Data were derived from downscaled projections from the 10 General Circulation Models (GCM) described in the fifth phase of the Coupled Model Intercomparison Project

(CMIP5) (Taylor et al. 2012). GCMs were statistically downscaled to 1/16th degree resolution using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown 2011). The 30-yr averages are often considered climatological normals that are not influenced by year-to-year variability for a given climate. Thus we used 30-year time windows of 1970-1999 (the 1980s) for historical runs and 2070-2099 (the 2080s) to estimate the projected changes for future time periods.

Data Sources
Gridded data for *summertime mean air temperature* in the study region were calculated from MACA-downscaled daily maximum and minimum air temperatures. We calculated daily means from daily maxima and minima from the 10 GCMs for each time period (historical and 2080s). From daily means, we calculated weekly means for each week during 16 Jul – 31 Aug. Gridded data for *mean annual precipitation* were calculated from MACA-downscaled monthly precipitation using water years Oct-Sep for historical and future time periods.

Gridded data for the *probability of winter precipitation falling as snow* were obtained from Klos et al. (2014). Time periods for this covariate differed: 1979-2012 (historical) and 2035-2065 (future). Thus, estimates of changes in this covariate are likely conservative for conditions expected in the 2080s.

Using a geographic information system (GIS), we attributed river reaches having TIR data with values from the gridded air temperature, precipitation, and snow probability datasets for use as covariates in random forest models.

Results
For both approaches, future water temperature increased overall, but change in thermal heterogeneity metrics was not as apparent. Assuming a homogeneous increase in water temperature, most patches remained of similar size and spacing; only the 90$^{th}$ percentile of warm patch size increased noticeably (Figure 7). Projected patterns in the 2080s assuming the RCP 8.5 climate change scenario included more cool habitat and larger cool patches than when we assumed a homogeneous increase of 3 °C (Table 1). Compared to historical patterns, warm patch length was longer but also more variable (Figure 8). Density of tolerable and warm patches decreased, whereas metrics remained similar for cool patches. We discuss progress on the process-based modeling in case study basins below.

### *Objective 3: Case study watersheds*

Siletz River, Oregon
In the proposal, we identified a suite of potential case study basins in which to focus our efforts. Based on feedback from NPLCC staff, we selected the Siletz River as the case study basin for Oregon. This watershed hosts threatened populations of coho and steelhead, coastal cutthroat populations that are candidates for ESA listing, the only native population of summer steelhead in the coast region, and healthy populations of Chinook and chum. The US Environmental Protection Agency and Oregon Department of Environmental Quality staff are currently developing a TMDL for rivers in this

watershed. Moreover, we have TIR data for a large number of tributaries and the mainstem.

We completed thermal heterogeneity analysis for streams in the Siletz. Instead of using temperature thresholds for each species (which are difficult to agree on), we applied 3 sets of generic thresholds that could be used to interpret habitat suitability for a variety of species. We defined warm/tolerable/cool habitat as (a) >22/17-22/<17 °C, (b) >20/15-20/<15 °C, and (c) >18/12-18/<12 °C. We evaluated the distribution of cool patches under historical and future scenarios using a homogeneous increase of 3 °C (simple approach) and conditions expected in the 2080s (random forest model).

We found a considerable amount of warmer habitat in the future when we assumed that water temperature warmed consistently by 3 °C (Figures 9 and 10). Cool patch density decreased, median patch size increased slightly, and spacing between patches increased (Table 1). However, changes predicted for the 2080s using the random forest model were not as dire (Table 1). The total amount of habitat considered cool was related to thermal thresholds; however, thermal heterogeneity metrics were less responsive (Table 1).

<u>Snoqualmie River, Washington</u>

On the Snoqualmie River, airborne TIR data were available for the mainstem and middle fork but not the tributaries. However, we selected the Snoqualmie because we hope to capitalize on synergies with related projects. For example, we have water temperature sensors deployed throughout the watershed (~40 sensors, 4 years of data so far, collected at 30-minute intervals). Using the spatial stream network model that was used to develop NorWeST predictions (Peterson and Ver Hoef 2010), we have predicted spatial patterns in water temperature across a range of temporal scales. We could use these data to characterize thermal heterogeneity, recognizing the caveats associated with using modeled data.

Second, several of the coauthors are involved in a project that is developing a physically based water temperature model in this watershed. We will use this model to simulate stream flow and water temperature for historical and future time periods. The simulated water temperature will be then used to identify thermal heterogeneity (i.e, prevalence, size, and spacing of cold patches). We will compare results with those produced from the simple and statistical frameworks described above.

The Distributed Hydrology Soil-Vegetation Model (DHSVM; Wigmosta et al. 1994, Sun et al. 2014) is a physically based, spatially distributed hydrological model that explicitly solves the water and energy balance and is typically implemented at a scale of 10-150 m (Figure 11). DHSVM uses digital elevation data to model topographic controls on air temperature, solar radiation, precipitation, and down-slope water movement. DHSVM also requires other spatially distributed land surface characteristics such as surface topography, vegetation cover, soil type and depth. In addition to the climate scenarios described above, we are considering an additional emissions pathway (RCP 4.5, a mid-range mitigation scenario; Taylor et al. 2012) and an additional future time period, the 2040s (2030-2059).

We are currently calibrating the DHSVM for the Snoqualmie-Snohomish River. Because the model has been previously applied in this watershed, we are starting with this model, and will use this watershed to identify a strategic approach for applying the model to the other case study basins.

Finally, A. Fullerton is also involved in a proposal (Pacific Northwest National Laboratory, lead) that hopes to use existing data to build a decision support system for local communities to evaluate the potential effects of extreme climate events.

Application in California

We have not applied our work in a California watershed because some previously unknown issues arose. First, water temperature stratifies in deep pools and is not captured well by TIR imagery in some of the candidate California rivers (this was not a problem in Washington and Oregon). This is a particular problem in the Eel River; moreover, our data did not overlap very well with areas of concern for fish in this river. Second, the climate modeling has not yet been completed for California, nor are NorWeST data available there yet. Finally, salmon at the southern end of their range have adapted to life history strategies that generally avoid summertime maximum temperatures; thus, our data may not be representative of stressful conditions for these fish.

We did get interest from partners working in the Russian and Eel Rivers. Most of the Russian River for which we have data falls outside the NPLCC boundary, and is privately owned. We have reasonably good data coverage in the Mattole River watershed, including some 303d-listed tributaries, so this may be a good place to focus in the future.

Products We Can Provide to Watershed Planners

For both historical and future scenarios, we characterize the size, spacing, density, and amount of cold water patches as:

1. Tables and graphs summarizing patterns across rivers within the watershed;
2. Individual longitudinal profile plots; and
3. Maps of suitable/tolerable/unsuitable patches for target species.

## Project Timeline

We are on schedule for meeting most goals outlined in the proposal. Most aspects of the first two objectives have been completed and we are working on a manuscript that encompasses these and additional Pacific Northwest rivers.

The third objective is on schedule. We have had conversations with parties involved in watershed planning in the Siletz and Snoqualmie watersheds on numerous occasions. We plan to meet in the coming months to showcase our results to date and to seek guidance about how our findings can be most useful. For DHSVM modeling, we plan to derive simulated water temperature and characterize thermal heterogeneity for the Snoqualmie River by Mar. 2016, and will complete work in other rivers by Feb. 2017.

One item that is taking longer than expected is development of models capable of predicting locations of cold-water patches based on their relationship with landscape drivers. We are seeking additional funding to pursue this question more holistically than will be possible as part of this project. Specifically, we discovered the need to bring in additional expertise by D. Miller. Thus, this aspect may not be completed by the end of the project; however, we fully intend to pursue this analysis. Meanwhile, we are focusing effort and time on development of the process-based model (DHSVM) in the case study watersheds. This shift in focus from the original proposal is actually more in line with our objectives of evaluating vulnerability of riverine thermal heterogeneity to climate change.

**Communication and Outreach**

We presented work from this project at the following venues: (1) the Environmental Protection Agency Region 10 (February 24 2015);, (2) the Climate Change Collaboration via webinar (March 24, 2015); (3) annual meeting of the California-Nevada chapter of the American Fisheries Society, Santa Cruz CA (April 10, 2015); (4) seminar at the National Marine Fisheries Service, Southwest Fisheries Science Center, Santa Cruz CA (July 13, 2015); (5) annual meeting of the American Fisheries Society, Portland OR (August 20, 2015) as part of the special session "Conserving cool- and cold-water lake and stream fishes through a warmer 21st century: Science, management, and policy needs" (Isaak, Jacobson, Hansen); and (6) seminar at the National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle (Oct 29, 2015), available here: https://nwfsc200.webex.com/nwfsc200/ldr.php?RCID=8d3dd6f3ec80a375f429f94c4a82ab3c.

Each of these presentations generated significant interest, especially in understanding how our research will help to define "sufficiently distributed cold water refuges". Specifically, our work should help the US Environmental Protection Agency and Oregon Department of Environmental Quality in their charge to "map and protect cold water refuges for fish in the Columbia and Willamette Rivers" that was recently called for in a Biological Opinion on Oregon temperature standards (http://yosemite.epa.gov/opa/admpress.nsf/0/7AC162A9568E994885257EF20077CC15).

We recently published a related paper describing whole-river patterns in water temperature and potential hydroclimatic drivers (Fullerton et al. 2015). We are currently drafting a manuscript describing within-river thermal heterogeneity throughout the Pacific Northwest.

**Signature**

Joshua Lawler, Project Manager

Date

Aimee H Fullerton

12/29/15

Aimee Fullerton, Co-PI

Date

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**Table 1.** Summary characteristics of cool water habitat for all rivers in the NPLCC, streams in the Siletz River basin, and streams in the Snoqualmie River basin under historical and future climate scenarios.

| Metric | Total length of cool habitat (km) | Cool patches per km | Cool patch length (km); median (10th and 90th percentiles) | Cool patch spacing (km); median (10th and 90th percentiles) |
|---|---|---|---|---|
| NPLCC (6,106 km surveyed, 4,211 km* of which is anadromous habitat) | | | | |
| Historical | | | | |
| < 17 ºC | 760.1 | 0.36 | 0.21 (0.06-4.76) | 0.24 (0.07-47.50) |
| < 15 ºC | 352.1 | 0.46 | 0.19 (0.06-4.71) | 0.24 (0.05-28.10) |
| < 12 ºC | 32.9 | 0.76 | 0.23 (0.12-2.04) | 0.69 (0.13-41.37) |
| Plus 3 ºC | | | | |
| < 17 ºC | 199.4 | 0.58 | 0.15 (0.05-2.79) | 0.26 (0.05-31.38) |
| < 15 ºC | 32.9 | 0.76 | 0.23 (0.12-2.04) | 0.69 (0.13-41.37) |
| < 12 ºC | 1.6 | 2.58 | 0.15 (0.11-0.86) | 11.14 (0.32-66.53) |
| 2080s | | | | |
| < 17 ºC | 545.2 | 0.30 | 0.30 (0.10-3.50) | 0.40 (0.10-8.60) |
| < 15 ºC | 229.3 | 0.46 | 0.30 (0.10-3.40) | 0.20 (0.10-4.90) |
| < 12 ºC | 23.1 | 0.30 | 0.90 (0.16-8.30) | 0.30 (0.10-34.0) |
| Siletz basin (219 km* surveyed, 197 km of which is anadromous habitat) | | | | |
| Historical | | | | |
| < 17 ºC | 124.6 | 0.45 | 0.29 (0.06-7.56) | 0.24 (0.05-2.11) |
| < 15 ºC | 48.7 | 0.70 | 0.25 (0.06-5.28) | 0.43 (0.06-7.10) |
| < 12 ºC | 14.8 | 0.41 | 1.75 (0.21-5.43) | 2.23 (0.15-49.81) |
| Plus 3 ºC | | | | |
| < 17 ºC | 29.2 | 0.62 | 0.40 (0.04-6.66) | 0.96 (0.08-13.2) |
| < 15 ºC | 14.8 | 0.41 | 1.75 (0.21-5.43) | 2.23 (0.15-49.81) |
| < 12 ºC | 0.73 | 2.74 | 0.37 (0.18-0.55) | 55.25 (17.70-92.79) |
| 2080s | | | | |
| < 17 ºC | 115.2 | 0.25 | 0.40 (0.10-12.2) | 0.70 (0.20-4.90) |
| < 15 ºC | 39.5 | 0.84 | 0.10 (0.10-4.30) | 0.20 (0.10-4.30) |
| < 12 ºC | 3.7 | 2.97 | 0.20 (0.10-0.70) | 0.20 (0.10-2.20) |
| Snoqualmie basin (103 km* surveyed, 63 km of which is anadromous habitat) | | | | |
| Historical | | | | |
| < 17 ºC | 19.4 | 0.93 | 0.35 (0.06-2.96) | 0.15 (0.10-5.61) |
| < 15 ºC | 0 | -- | -- | -- |
| < 12 ºC | 0 | -- | -- | -- |
| Plus 3 ºC | | | | |
| < 17 ºC | 0 | -- | -- | -- |
| < 15 ºC | 0 | -- | -- | -- |
| < 12 ºC | 0 | -- | -- | -- |
| 2080s | | | | |
| < 17 ºC | 1.8 | 3.33 | 0.20 (0.10-0.60) | 1.60 (0.90-64.5) |
| < 15 ºC | 0 | -- | -- | -- |
| < 12 ºC | 0 | -- | -- | -- |

*reported here

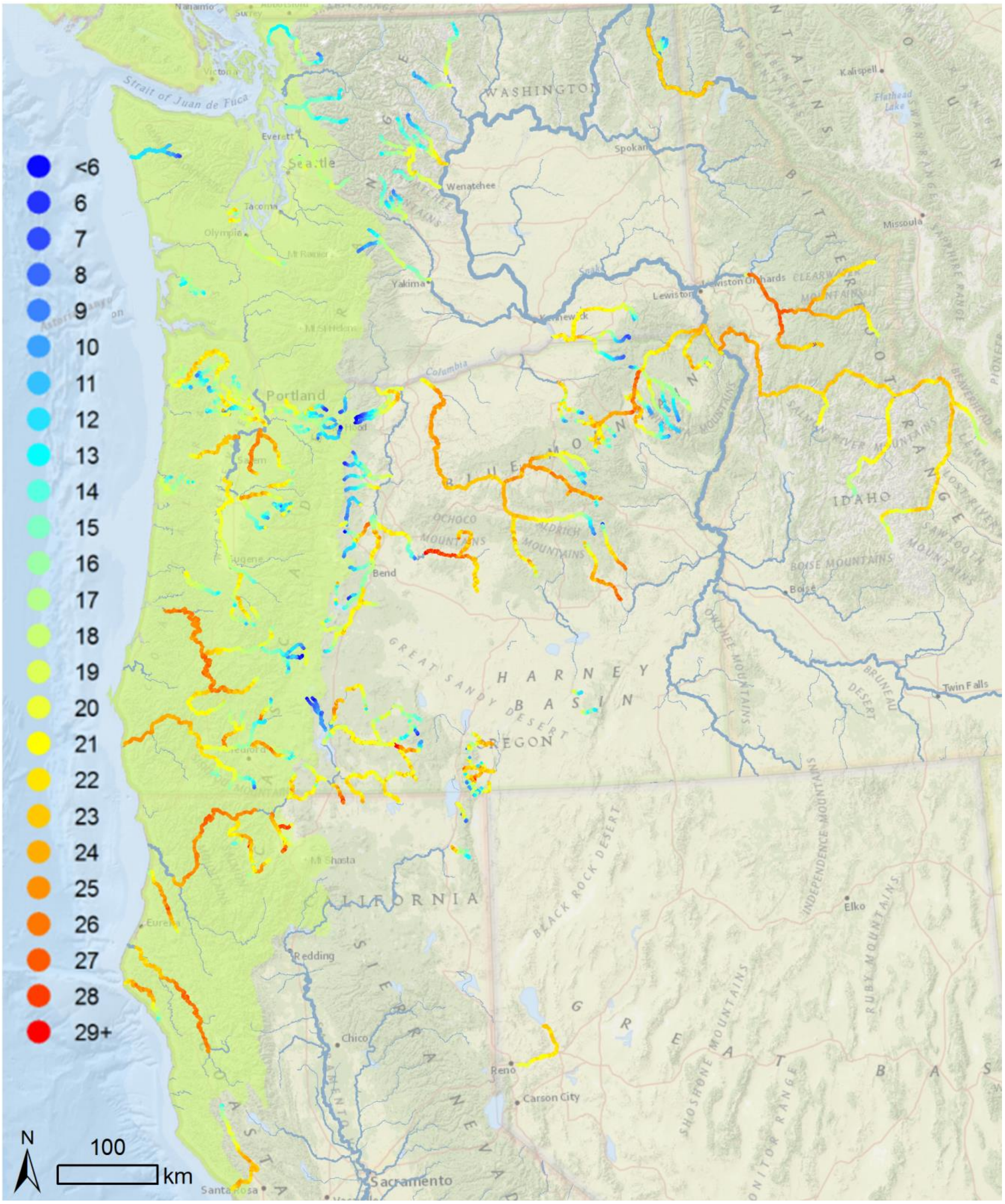


**Figure 1.** Thermal infrared surveys of afternoon summer water temperature (°C) in rivers throughout the Pacific Northwest and California. Results in this report are for 6,106 km of rivers within the North Pacific Landscape Conservation Cooperative domain (green).

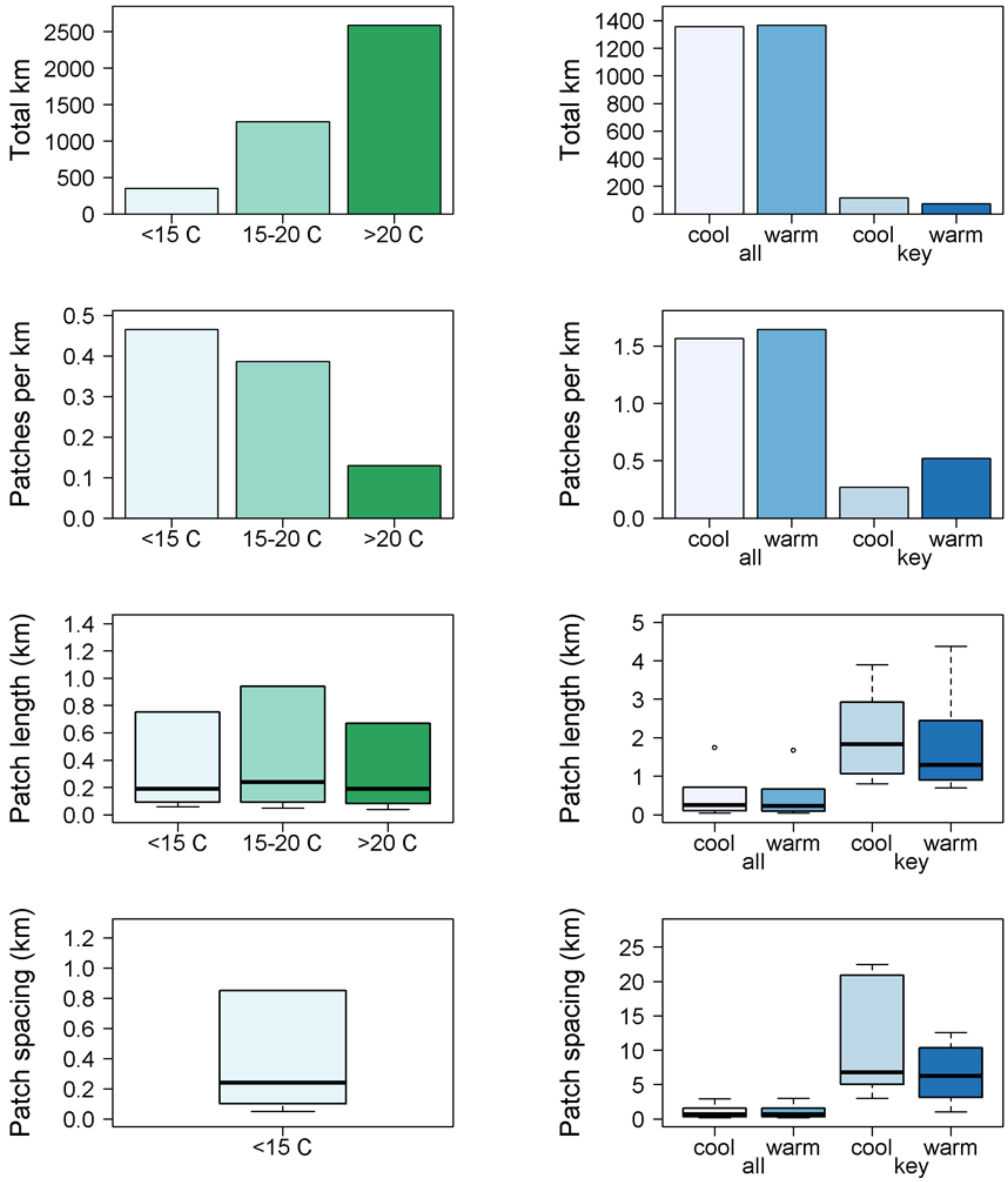


**Figure 2.** Metrics of thermal heterogeneity, summarizing anadromous habitat in rivers within the NPLCC boundary for which TIR data were available (6,106 km). **Left column:** Thermal heterogeneity quantified by slicing longitudinal profiles into 3 thermal zones. **Right column:** Thermal heterogeneity within portions of rivers exceeding 20 °C, quantified as peaks (warm patches) and valleys (cool patches) from a moving average trend. Key patches were at least 500-m long and had temperature differentials of 2 °C or greater.

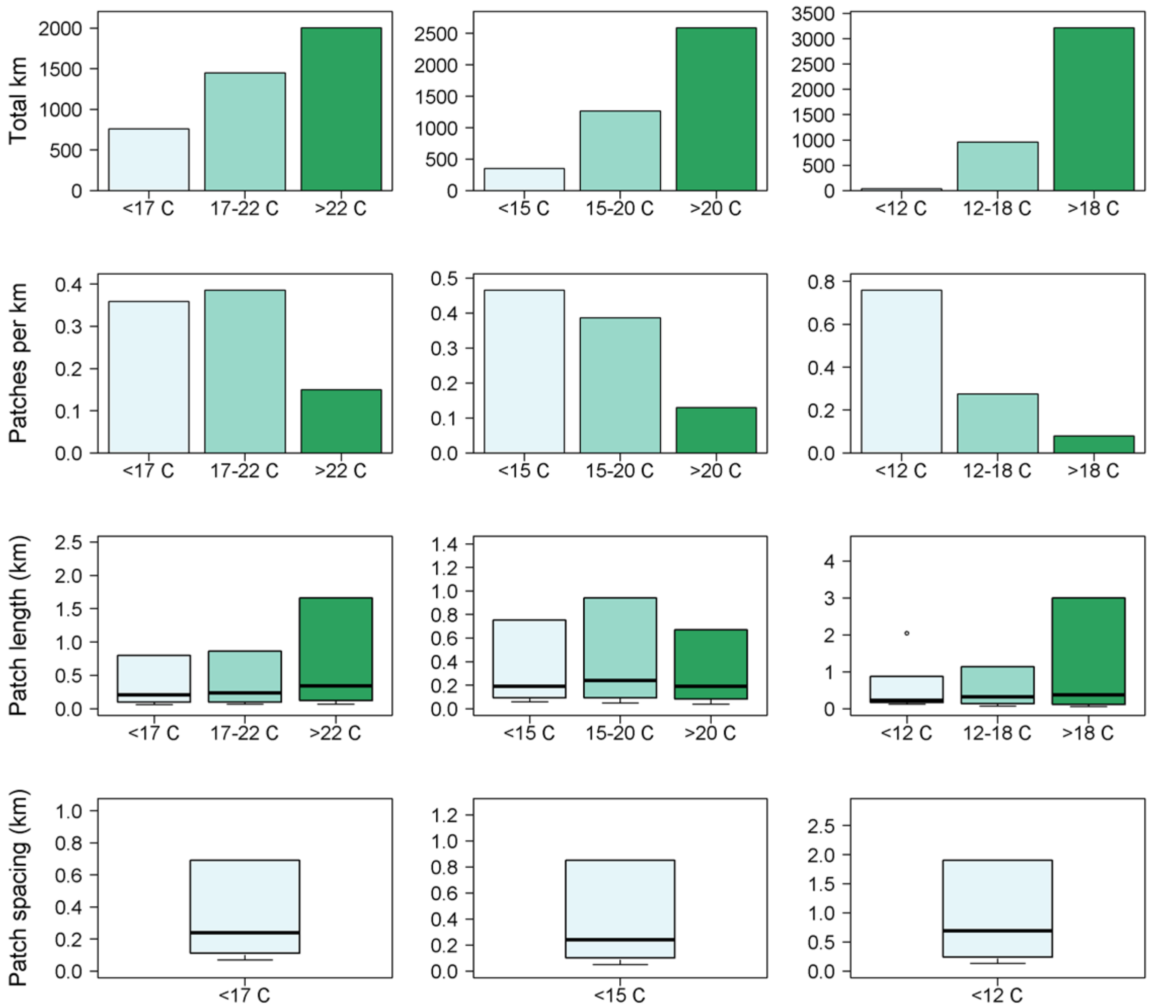


**Figure 3.** Metrics of thermal heterogeneity for three different sets of thresholds that might be associated with a warm-tolerant species such as rainbow trout (**left column**), a mid-range species such as coho salmon (**middle column**), or a species with narrower thermal tolerances such as certain races of Chinook salmon (**right column**). Thermal tolerances and preferences within a species differ regionally. Note the different y-axes for each metric across columns.

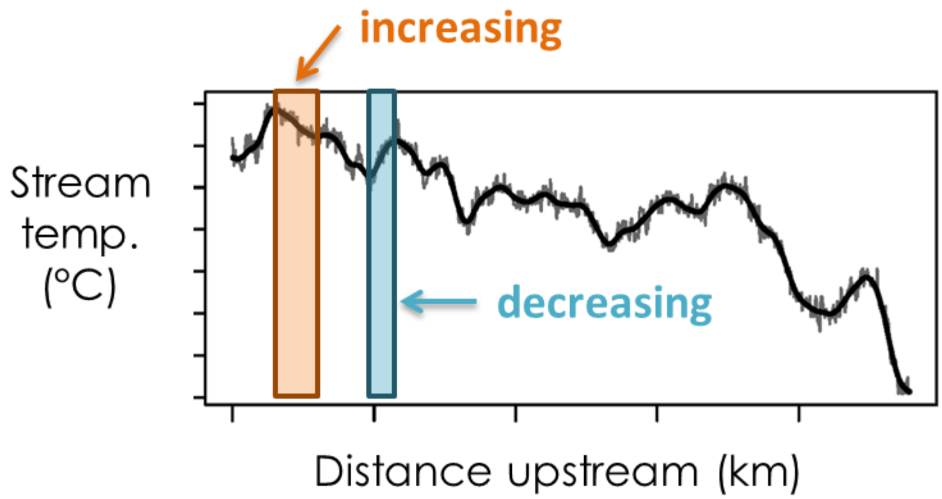


**Figure 4.** Illustration of locations along a longitudinal profile where temperature is decreasing (increasing) in a downstream direction. These are the locations that we will associate with potential drivers.

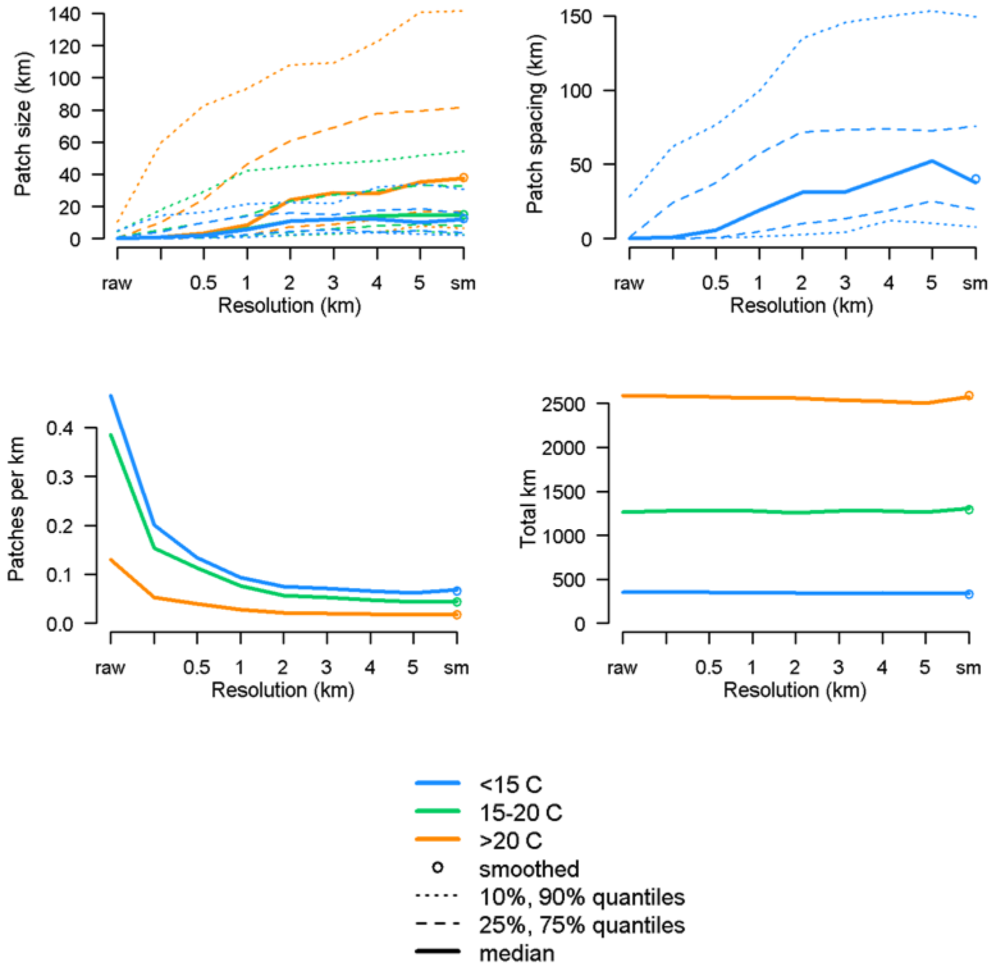


**Figure 5.** Thermal heterogeneity metrics (y axes), quantified by slicing longitudinal profiles into 3 thermal zones, plotted across decreasing resolution of water temperature data (x axes). Data included anadromous habitat in rivers within the NPLCC boundary for which TIR data were available (6,106 km). Raw = original TIR data resolution; sm = smoothed.

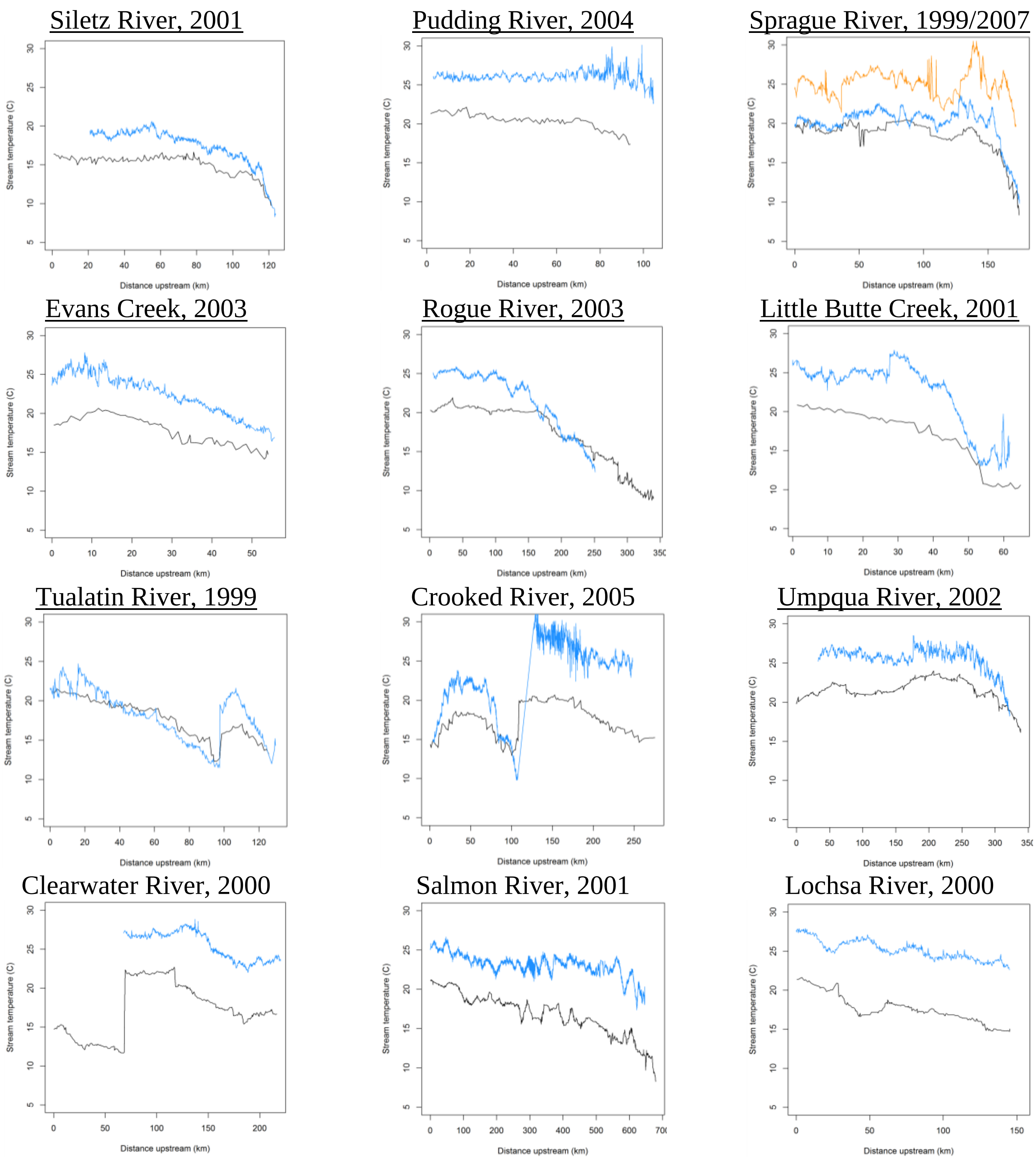


**Figure 6.** Comparison of profiles constructed from thermal infrared surveys, colored lines, and from modeled mean August (1993-2011) water temperature (NorWeST), black lines. Rivers underlined are within the NPLCC boundary. Rivers shown were selected because both types of data were available and distances were long enough to compare spatial patterns.

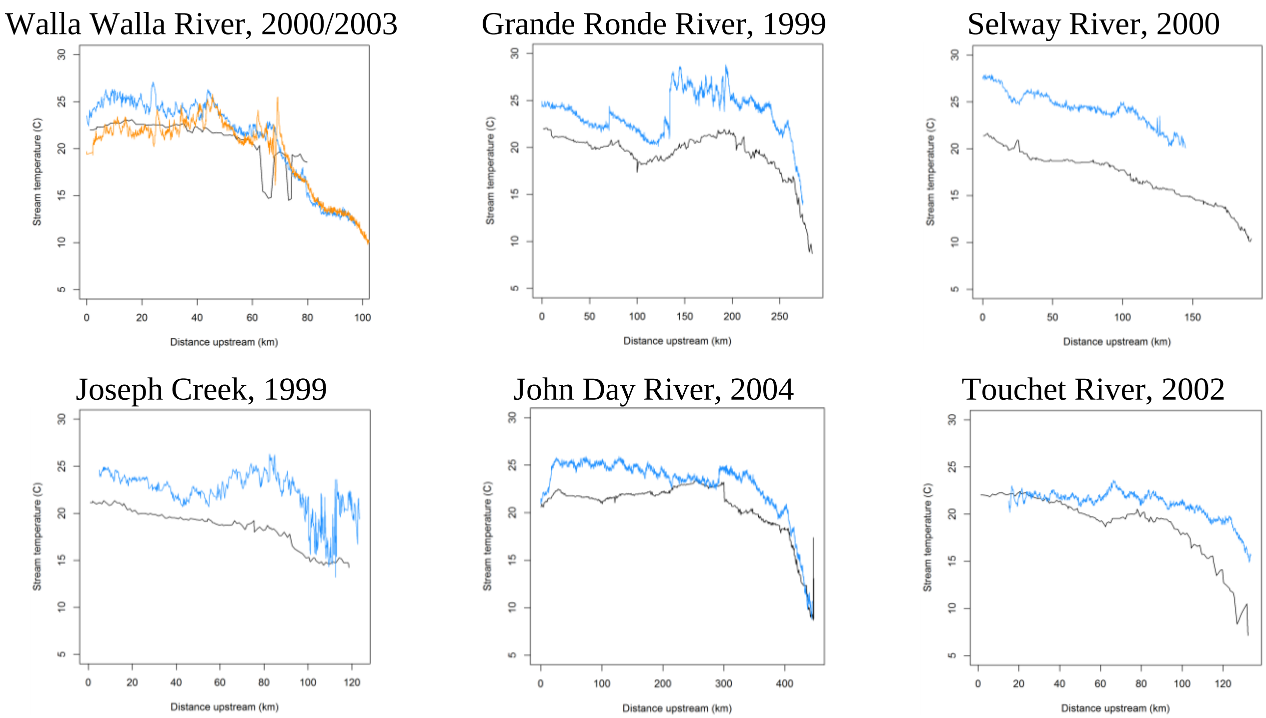


**Figure 6.** Continued.

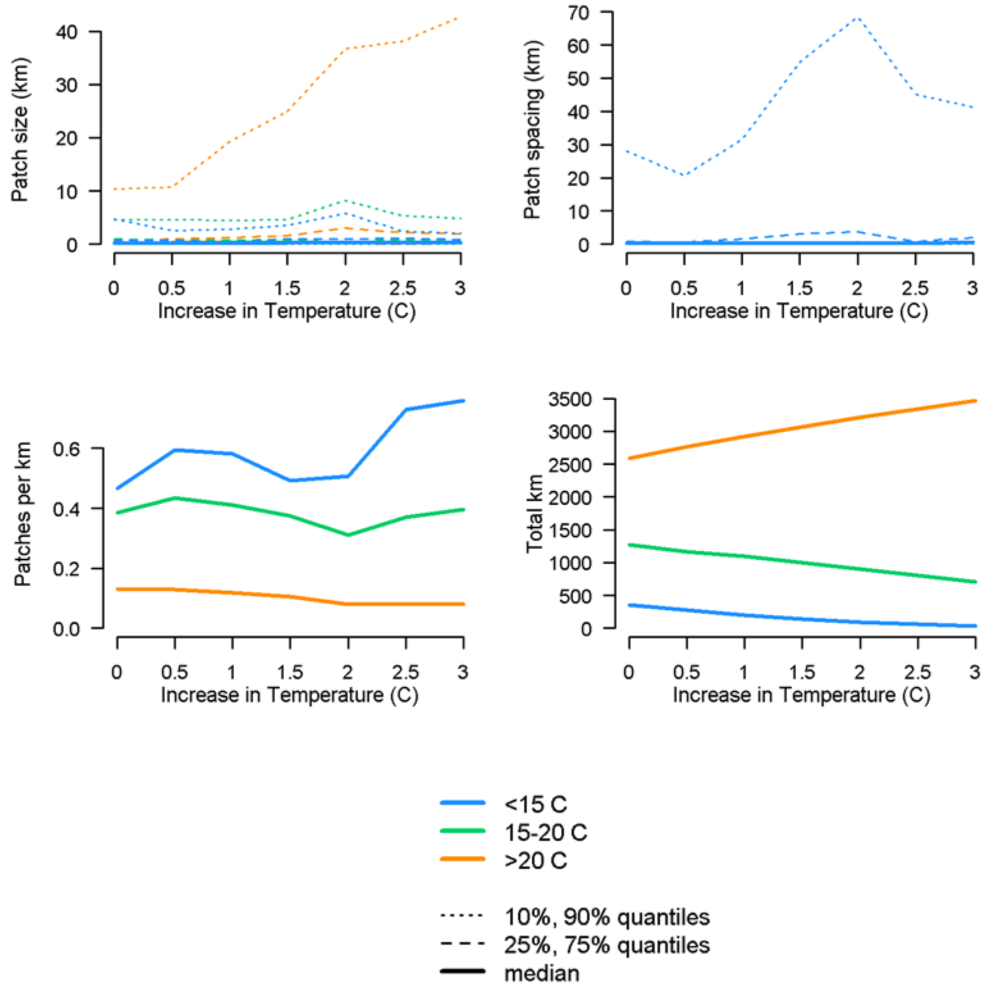


**Figure 7.** Thermal heterogeneity metrics (y axes), quantified by slicing longitudinal profiles into 3 thermal zones, plotted across scenarios of homogenously increasing water temperature by a given amount (x axes). Data included anadromous habitat in rivers within the NPLCC boundary for which TIR data were available (6,106 km).

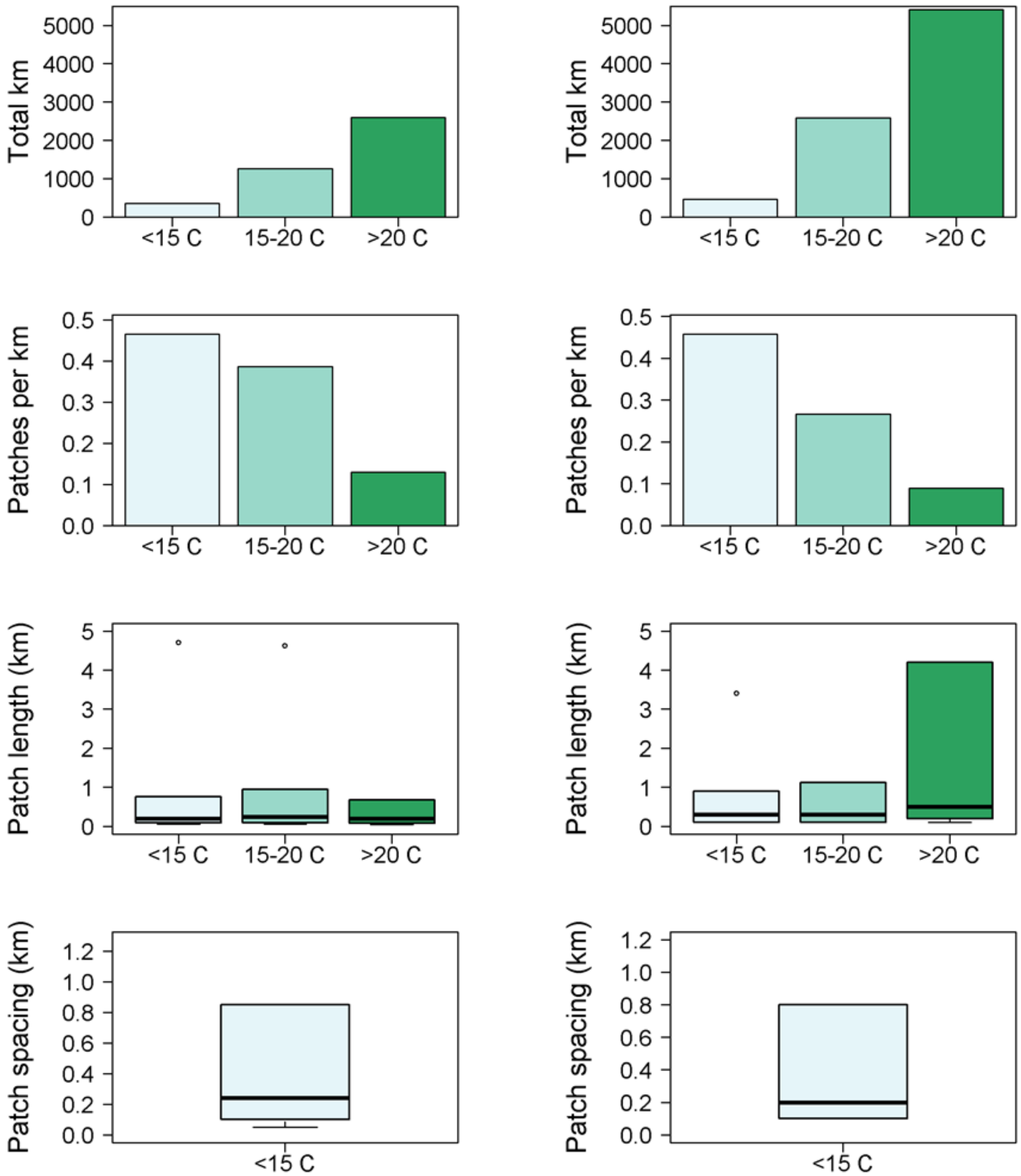


**Figure 8.** Metrics of thermal heterogeneity, quantified by slicing longitudinal profiles into 3 thermal zones. Data included anadromous habitat in rivers within the NPLCC boundary for which TIR data were available (6,106 km). **Left column:** Original TIR data. **Right column:** Projected patterns in the 2080s assuming the RCP 8.5 climate change scenario.

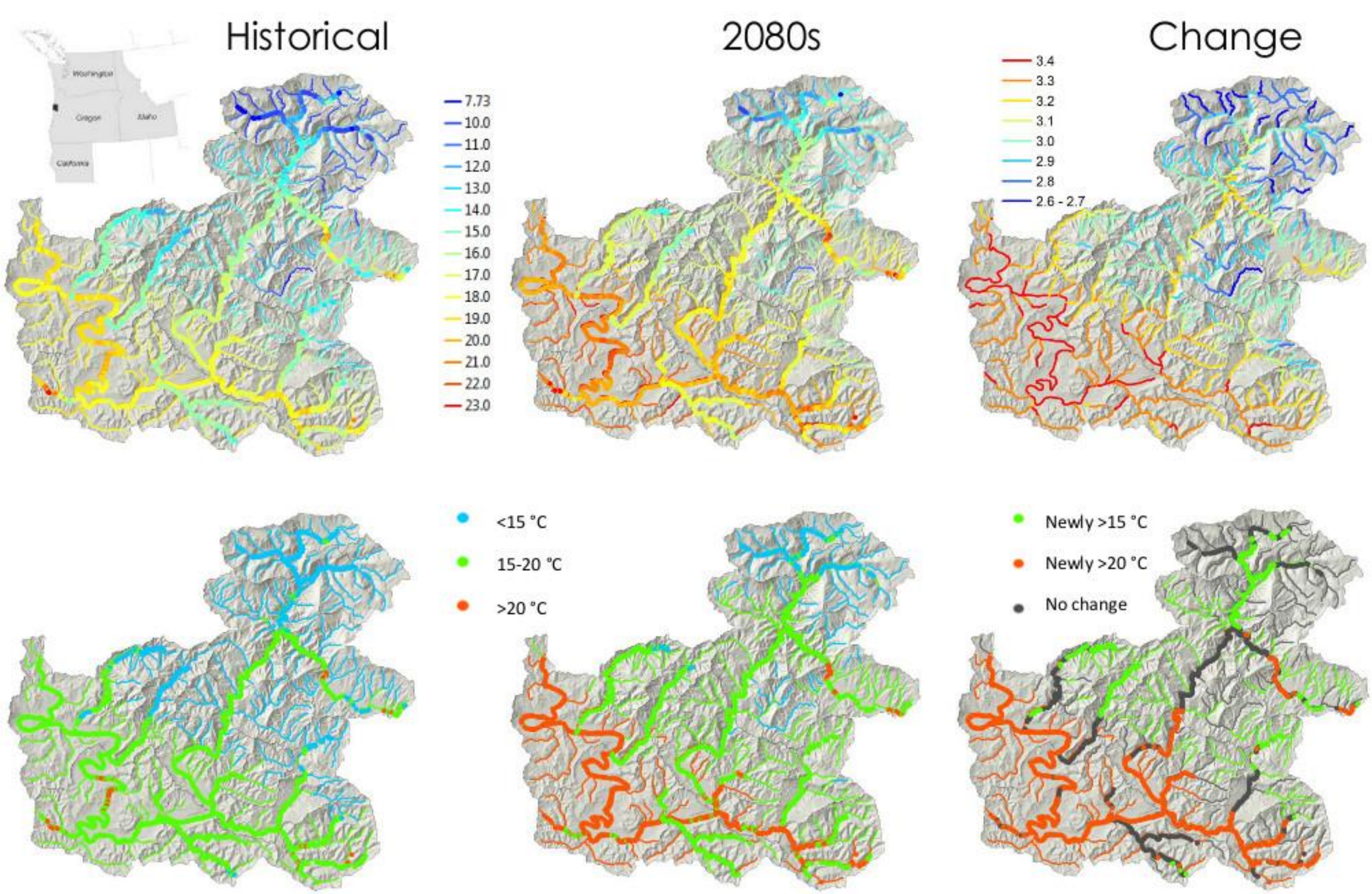


**Figure 9.** Siletz River watershed, Oregon. **Top row**: maximum summer water temperature measured by thermal infrared (TIR; thick lines) and estimated from NorWeST (thin lines) during August in 2001 (**left**), potential future conditions if water temperature rises by 3 ºC (**middle**), and the difference between historical and future temperatures (NorWeST only; **right**). **Bottom row**: water temperature binned into three zones according to suitability for general salmonids: <15 ºC (good), 15-20 ºC (fair), and >20 ºC (poor) during August 2001 (**left**), assuming temperatures warm by 3 ºC (**middle**), and locations that shift from cool to moderate or from moderate to warm (**right**). PDF of this image available separately.

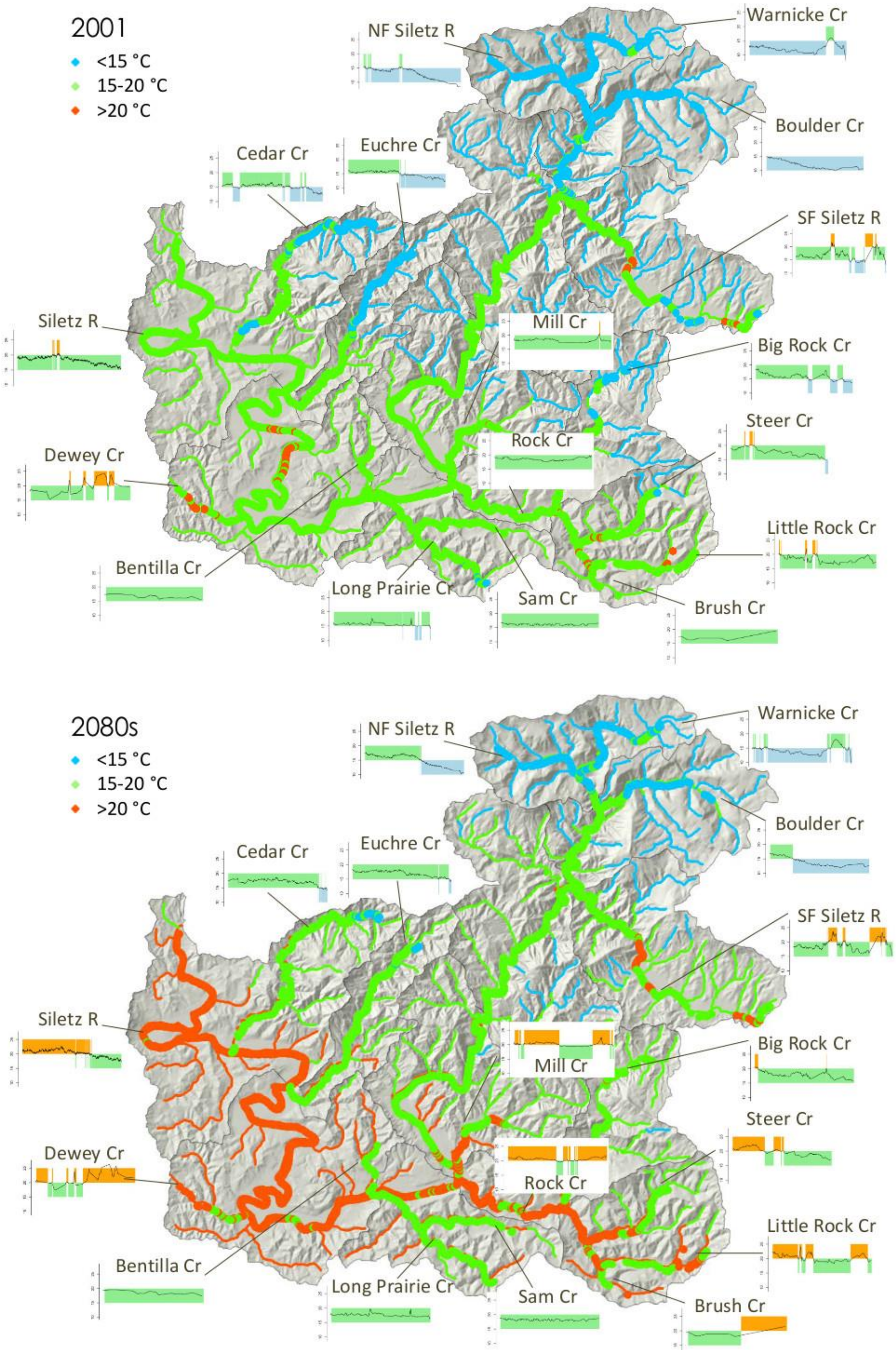


**Figure 10**. Water temperature binned into zones of <15 ºC (good), 15-20 ºC (fair), and >20 ºC (poor) during August 2001 (**top**), and assuming temperatures warm by 3 ºC (**bottom**). Inset plots are longitudinal profiles of water temperature for each stream where we had TIR data (y-axis: water temperature, x-axis: distance upstream).

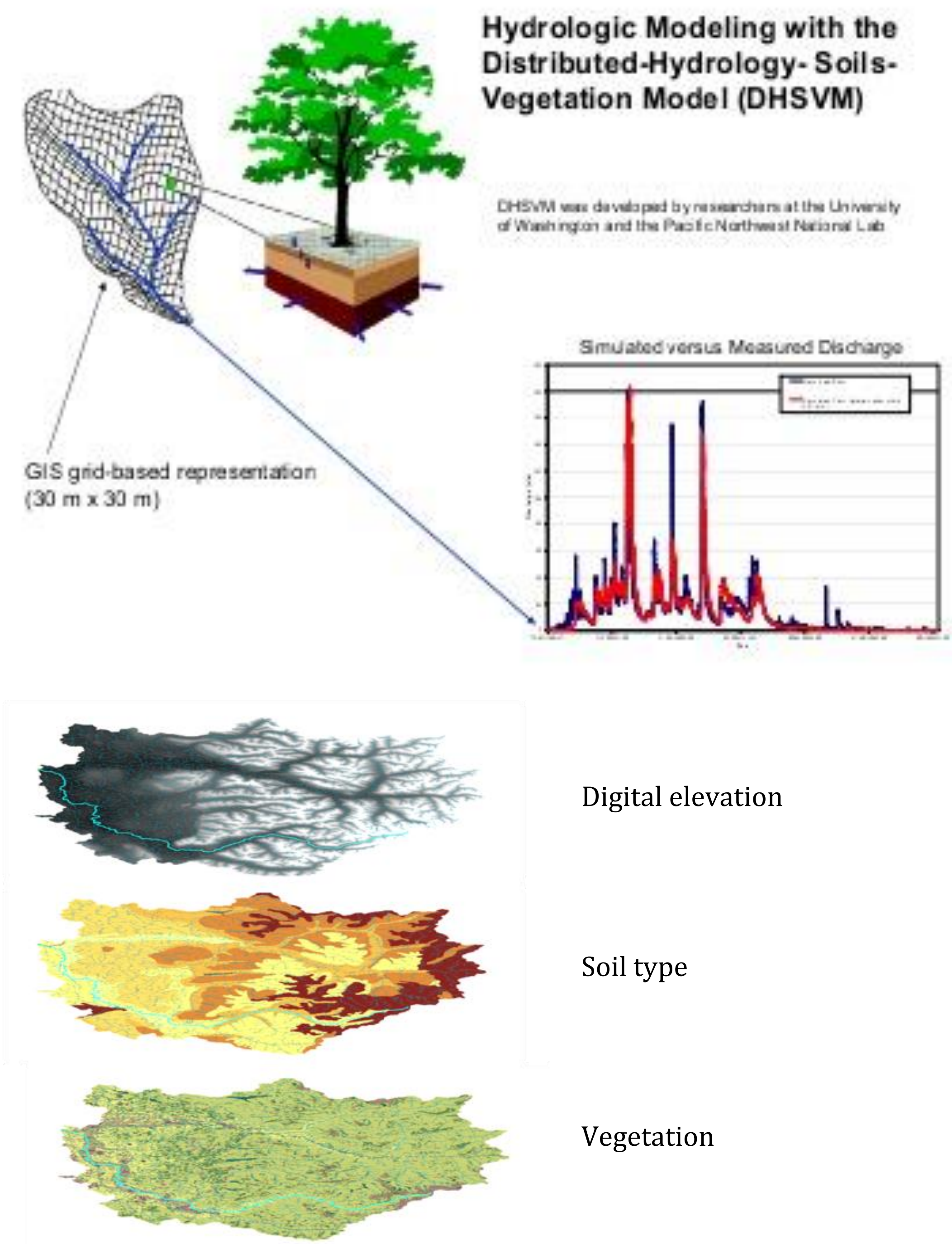


**Figure 11.** Schematic (top) and inputs (bottom) of the DHSVM.