Analysis of Spatial Stream Networks for Salmonids

Fish Data Analysis Tool, Phase 2 Report

BPA Project 2017-002-00

Report covers work performed under BPA contract #81163 and #81603

Report covers work performed from: December, 2018 – February, 2020

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Report Created: April, 2020

"This report was funded by the Bonneville Power Administration (BPA), U.S. Department of Energy, as part of BPA's program to protect, mitigate, and enhance fish and wildlife affected by the development and operation of hydroelectric facilities on the Columbia River and its tributaries. The views in this report are the author's and do not necessarily represent the views of BPA."

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Deliverable 2. ArcGIS shapefiles containing juvenile steelhead salmon density observations, twenty-four SSN modelled density scenarios mapped to 250-m prediction points, twenty-four SSN modelled density scenarios mapped to 250-m reach segments, and covariate values at the observation and prediction sites (Filename: FDAT_Phase2_Steelhead_FinalShapefiles&Metadata.zip).

Deliverable 3. R code and .ssn directory files to replicate SSN analysis of juvenile Chinook salmon dataset (Filename: FDAT_Phase2_ChinookFullLSN-STB.ssn)

Deliverable 4. R code and .ssn directory files to replicate SSN analysis of juvenile steelhead dataset (Filename: FDAT_Phase2_SteelheadFullLSN-STB.ssn).

Abstract

The Bonneville Power Administration and partner agencies have made significant investments in monitoring juvenile anadromous fish populations within the Columbia River Basin in previous decades. Thousands of reach surveys have been conducted to determine local densities of Chinook salmon and steelhead. Because multiple agencies collect these data for different purposes, fish survey sites are spread widely within and among basins, and some sites are resampled annually to describe temporal trends. Aggregation of these surveys into a large database provides a considerable resource, which among many possible uses, can be used with Spatial Statistical Network (SSN) models to develop new information about patterns in juvenile densities and covariates that affect those patterns. In Phase 1 of the Analysis of Spatial Stream Networks for Salmonids project (BPA contract #77234), we tested the application of SSN models to juvenile Chinook salmon and steelhead trout density surveys from the Grande Ronde and Wallowa River basins in northeastern Oregon (project area: 10,642 km^2). Results from the Phase 1 analysis were sufficiently promising that Phase 2 was implemented to expand the approach to a larger geographic area that included the John Day and Imnaha river basins of Oregon, as well as all streams accessible to anadromous fish in Idaho (project area: 90,822 km^2). Large datasets of juvenile fish surveys for Chinook salmon (n = 6,757) and steelhead (n = 7,436) were aggregated from CRITFC, ODFW, IDFG, USFS, CHaMP, and BioMark for the period of 2000–2018. These data were fit with SSN models and 28 covariates were assessed, which included representations of summer temperatures, flow characteristics, channel type, riparian conditions, land-use, land-cover, geology, invasive species, and inter-annual variation in juvenile densities. The final model for Chinook salmon juvenile densities included statistically significant relationships for seven covariates (reach slope, mean summer flow, mean August stream temperature, baseflow index, riparian canopy density, brook trout density, and inter-annual variation in juvenile densities) and explained 57% of the variation in densities at the survey sites across a potential habitat network of 9,064 km. The final model for steelhead accounted for 48% of the variation in densities at the survey sites across a larger potential habitat network of 18,064 km. The steelhead model included six of the same seven covariates as the Chinook salmon model (watershed conifer coverage replaced baseflow index) but response curves indicated different density-habitat relationships between the two species. Chinook salmon densities were highest in medium sized streams and rivers with low reach slopes, cool temperatures, higher brook trout densities, and intermediate levels of riparian canopy cover and baseflow values. Steelhead densities were highest in small streams with higher slopes, warmer temperatures, low brook trout densities, higher proportions of watershed conifer coverage, and intermediate levels of riparian canopy density. The final models were used to create 24 scenarios of juvenile densities throughout the potential habitat networks, which included a baseline composite scenario of average juvenile densities for 2000-2018 (Scenario 1), annual density scenarios from 2000 through 2018 (Scenarios 2–20), standard errors of the density predictions (Scenario 21), and three future density scenarios associated with increases in mean August stream temperature of 1°C, 2°C, and 3°C (Scenarios 22–24). The scenarios have many potential applications, a few of which are illustrated by calculating population estimates of juvenile Chinook salmon and steelhead by designated population areas and by assessing the sensitivity of juvenile densities to a 2°C increase in August temperatures. The observation datasets of juvenile densities, as well as the predicted density scenarios, were formatted and delivered with this report as ArcGIS shapefiles to facilitate further applications. A companion report done under BPA contract #81134 addresses additional work elements and explores options for open-source and cloud-based spatial data processing, modeling, and visualization of data and results associated with the Analysis of Spatial Stream Networks for Salmonids project.

Introduction

Significant investments have been made by the Bonneville Power Administration (BPA) and partner agencies to monitor anadromous fish populations and restore habitats within the Columbia River Basin in previous decades. Spatially indexed juvenile salmon and steelhead density surveys now exist at thousands of sites throughout the region. These counts are valuable for answering the status and trend questions that originally motivated collection of the datasets, but the data can also be repurposed at low cost for use with geospatial descriptions of stream covariates (e.g. slope, elevation, land use) and spatial-stream-network (SSN) models (Ver Hoef et al. 2006; Ver Hoef and Peterson 2010) to understand factors that affect densities and to make predictions of fish densities beyond observation sites to encompass full river networks (Isaak et al. 2017a). Predicted densities can also be integrated over full networks or subdomains within networks to obtain population estimates at a variety of spatial scales that are relevant to conservation and investment planning. SSN models differ from other types of models in that they do not require spatially independent samples, but instead benefit from non-independence and spatial clustering among survey locations. This flexibility allows SSNs to make use of data from multiple sources and incentivizes the development of consistent, centralized databases because the accuracy of model predictions improves as the amount of data and site clustering in modeled datasets increase.

The goal of the Analysis of Spatial Stream Networks for Salmonids RM&E research project is to develop the means of applying SSNs in an automated, computationally efficient, and consistent manner to anadromous fish juvenile density datasets; with the ultimate goal of displaying quantitative field results and modelled abundance and distribution information to help guide salmonid resource management and habitat restoration actions. In Phase 1 of the project (Peterson et al. 2018), juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*) density data collected by CRITFC and ODFW from sites in the Grande Ronde river basin in northeastern Oregon were fit with SSN models to a small set of stream covariates to determine whether the density data exhibited spatial autocorrelation and the potential utility of SSN model applications. Model fitting and data visualization were also integrated to a Fish Data Analysis Tool (FDAT) that automated several processes and ported output information to an online data viewer.

Results from the Phase 1 pilot analysis were deemed sufficiently promising that Phase 2 was implemented to expand the approach to a larger geographic area that included the John Day and Imnaha river basins of Oregon, as well as all streams accessible to anadromous fish in Idaho. This broadened scope enabled the aggregation of larger fish survey datasets from a more diverse range of stream and environmental conditions, so a key objective in Phase 2 was assessment of a large suite of stream covariates in an attempt to develop SSN models that were ecologically realistic. Final SSN models could then be used to create accurate prediction maps and scenarios of juvenile fish densities during historical and future periods throughout the river networks within the Phase 2 project area. These scenarios have many potential applications, which are illustrated by calculating population estimates of juvenile Chinook salmon and steelhead by designated population areas and by assessing the sensitivity of spatial patterns in juvenile densities to a future increase in August stream temperatures. A companion report done under BPA contract #81134 addresses additional work elements relating specifically to FDAT by exploring options for open-source and cloud-based spatial data processing, modeling, and visualization of data and results. Links to additional datasets, tools, methods, and protocols developed in association with this project are contained in Appendix A.

Methods

Project area

The Phase 2 project area includes northeastern Oregon, a small portion of southeastern Washington, and central Idaho (Figure 1). The area encompasses 90,822 km^2 and is drained by several major rivers which include the Grande Ronde, Wallowa, Imnaha, John Day, Clearwater, and Salmon. Elevations range from 80 m to 3,800 m and physiography varies from mountains to valley plains with mesic to arid climatic conditions. Higher elevations and topographically steep areas are publically owned and administered by the U.S. Forest Service and Bureau of Land Management; whereas valley bottoms are privately or tribally owned and used for agricultural, ranching, and subsistence purposes.

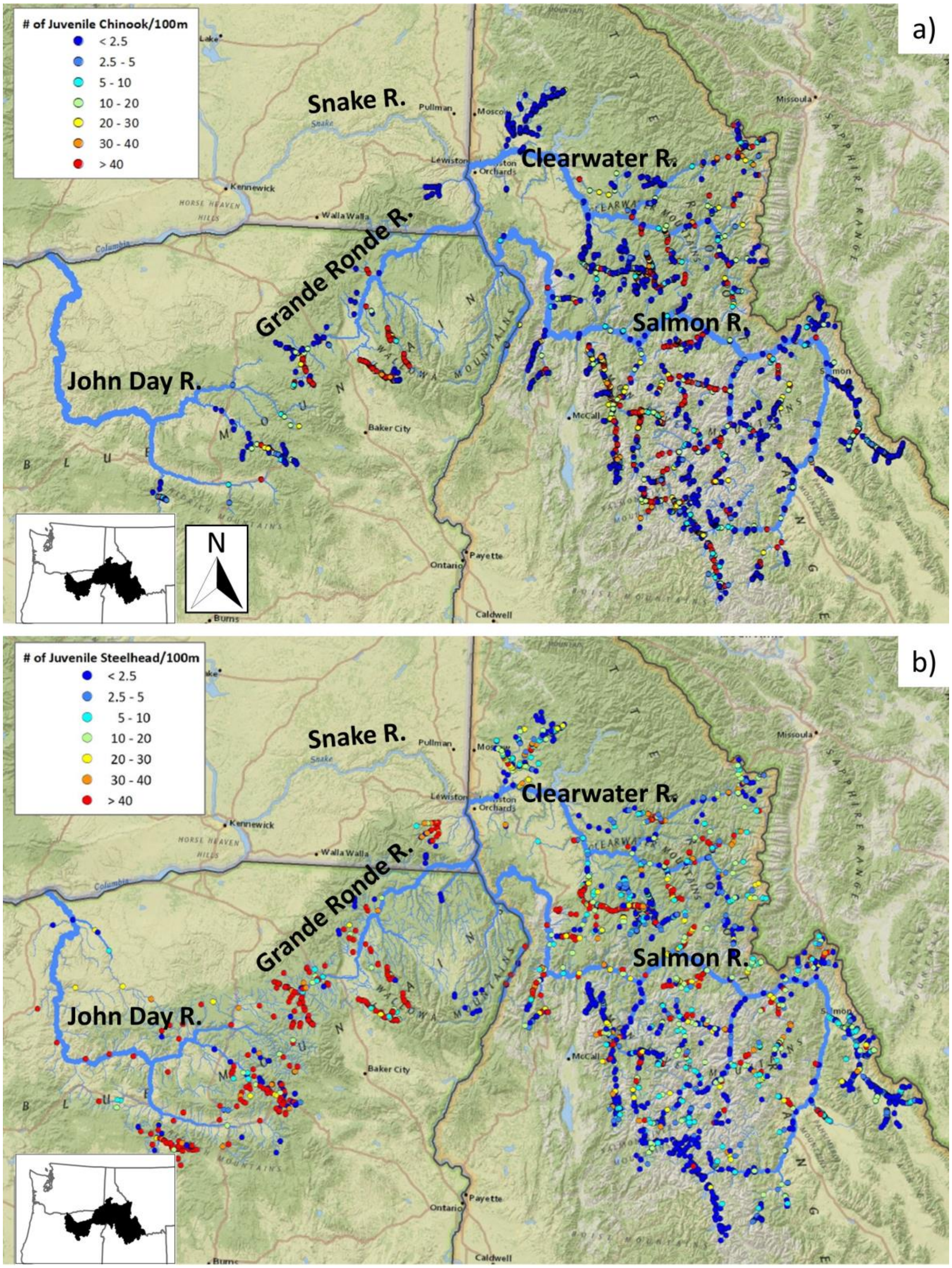

Figure 1. Fish densities at sample locations for juvenile Chinook salmon (panel a; n = 6,757 surveys at 2,307 unique stream sites) and steelhead (panel b; n = 7,436 surveys at 2,797 unique sites) from 2000 to 2018 that were aggregated from partner agencies to develop SSN models and fish density prediction scenarios for this report. Many of the locations were repeatedly sampled and locations depicted on the map show density values for the most recent survey year.

Fish density data

Juvenile survey data for Chinook salmon and steelhead were solicited from partner agencies and assembled into a consistent dataset format for analysis. Survey data were contributed by the Oregon Department of Fish and Wildlife (ODFW), Columbia River Intertribal Fish Commission (CRITFC), Idaho Fish and Game Department (IDFG), BioMark, the Columbia Habitat Monitoring Program (CHaMP 2016), and U.S. Forest Service (USFS). For Chinook salmon, data were available from 2,307 unique locations, many of which were repeatedly sampled during 2000–2018, to provide a total of 6,757 observations (Table 1; Figure 1). Data for steelhead were available from 2,797 unique locations, many of which were also repeatedly sampled during the same period, to provide a total of 7,436 observations (Table 1; Figure 1). Fish surveys were conducted primarily by snorkeling and to a lesser degree by electrofishing, through reaches that varied in length and used methodologies specified by each agency. To create a standardized juvenile density dataset from the survey information, numbers of Chinook salmon and steelhead less than 150 mm in length that were counted or estimated to occur within reaches were translated to linear density values as the number of fish per 100 m of stream.

Because the number of adults returning to spawn varies considerably among years, it was expected that juvenile densities would also show temporal variability during the 19 year span of data. Therefore, average annual densities of juvenile Chinook salmon and steelhead were calculated across all survey sites by year. Summaries indicated that annual densities peaked for both species during 2001–2005 with a smaller, less dramatic peak during 2011–2016 (Figure 2). This temporal variability generally matches observations reported from other studies for this area in recent decades (Isaak and Thurow 2006; Copeland and Meyer 2011) and was incorporated to the SSN models as described below to maximize predictive accuracy.

Geospatial stream networks

The midpoints of fish density survey reaches were linked to a vector stream network within the Phase 2 area that was downloaded from the National Stream Internet website (NSI; www.fs.fed.us/rm/boise/AWAE/projects/NationalStreamInternet.html; Nagel et al. 2015). The NSI network is a derivative of the 1:100,000 scale NHDPlusV2 network (McKay et al. 2012), has been topologically adjusted to facilitate SSN analysis using the Spatial Tools for the Analysis

Table 1. Sources and numbers of juvenile fish density data surveys that were aggregated to create the datasets modeled in this report.

Species	Data source	Unique stream sites	Site-years of data
Chinook salmon	ODFW	56	100
	FDAT Phase 1 (CRITFC, ODFW, CHaMP)	131	330
	IDFG	1594	5,556
	IDFG - ISEMP	469	682
	BioMark Kevin See	21	23
	U.S. Forest Service[a]	51	66
	Totals:	2,307	6,757
Steelhead	ODFW	161	270
	FDAT Phase 1 (CRITFC, ODFW, and CHaMP)	148	366
	IDFG	1,727	5,744
	IDFG – ISEMP	657	937
	BioMark Kevin See	21	23
	U.S. Forest Service[a]	81	96
	Totals:	2,797	7,436

[a]Queried from the U.S. Forest Service Natural Resource Monitor database: http://fs.fed.us/nrm/,

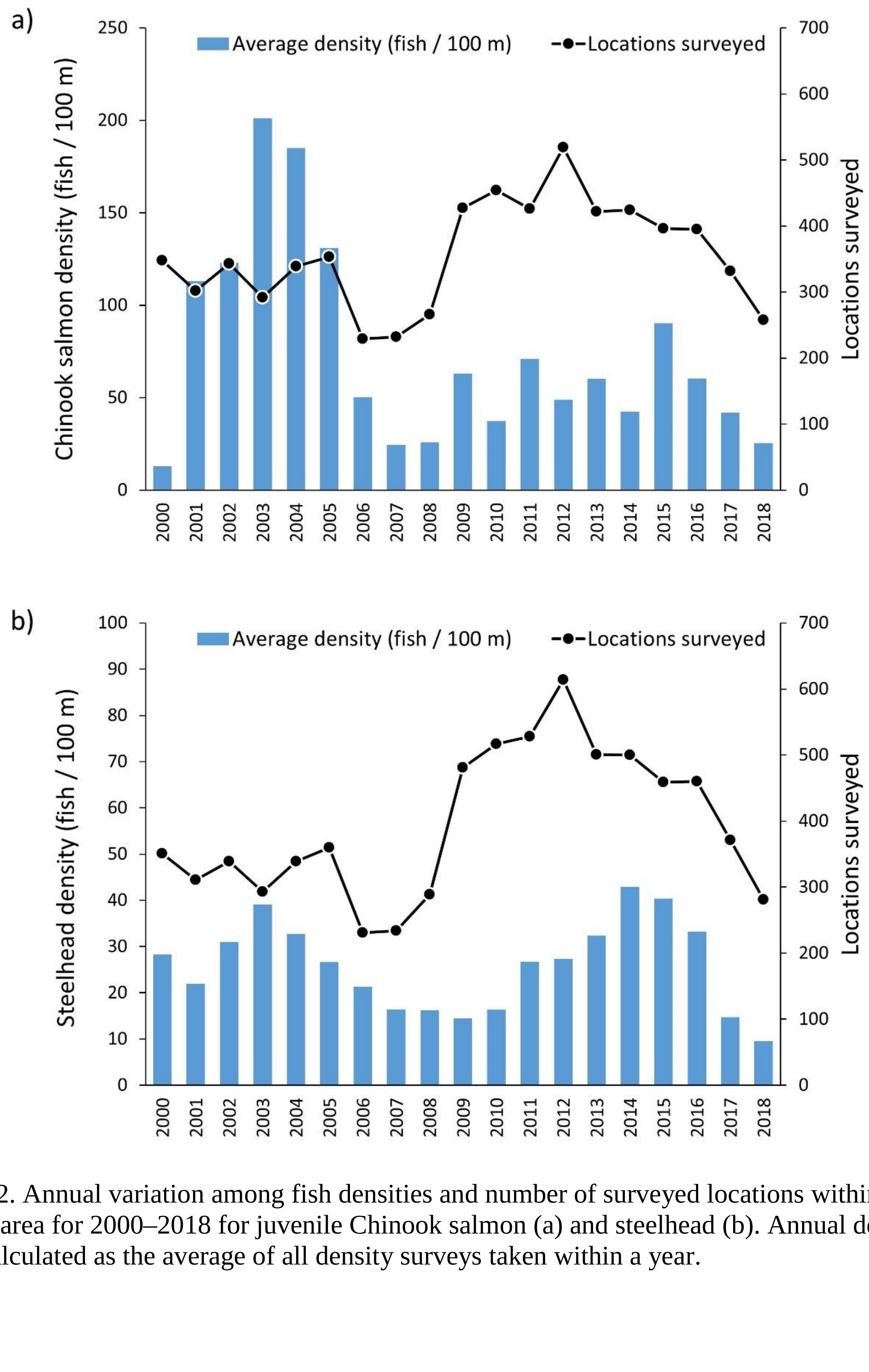

Figure 2. Annual variation among fish densities and number of surveyed locations within the project area for 2000–2018 for juvenile Chinook salmon (a) and steelhead (b). Annual densities were calculated as the average of all density surveys taken within a year.

of River Systems software (STARS; Peterson and Ver Hoef 2014), and is available for all streams and rivers in the coterminous U.S. The NSI network within the Phase 2 area included many streams that were too steep or small to serve as potential habitat for Chinook salmon and steelhead. Therefore, the NSI network was trimmed to match the StreamNet (https://www.streamnet.org/) distribution layers for these species. For Chinook salmon within the Grande Ronde basin, the extent of potential habitat reaches was expanded based on information provided by CRITFC biologists (Seth White and Casey Justice, unpublished data) during Phase 1. We also expanded the potential habitat networks where the fish survey data indicated the occurrence of either target species outside the StreamNet distribution layers. Locations of those additional reaches are shown in Appendix B, and they should be considered for inclusion to future StreamNet revisions (geospatial descriptions of these reaches are available from the authors upon request). The lengths of NSI reach additions to StreamNet exclusive of those done previously in the Grande Ronde basin during Phase 1 were 381 km and 580 km for Chinook salmon and steelhead, respectively. The final extents of the potential habitat networks used in SSN analyses for Phase 2 were 9,064 km for Chinook salmon and 18,064 km for steelhead as shown in Appendix B. Population areas for 35 spring/summer Chinook salmon populations and 29 steelhead populations were also designated for subdomains within the final networks (Appendix C) using NOAA's West Coast Region Salmon and Steelhead Geodatabase (Version 1.0) to assist with result summaries.

Covariates

To be usable in the SSN analysis, covariates with the potential to affect juvenile salmonid densities had to be available as geospatial data layers that spanned the fish survey sites and extents of the Phase 2 potential habitat networks. Twenty-six covariates were considered, which included measures of summer stream temperature, flow characteristics, channel type, riparian conditions, land-use and land-cover types, geologic attributes of watersheds, and occurrence of two invasive species (brook trout and smallmouth bass). Covariate geospatial layers were obtained from a variety of sources and detailed descriptions of these sources and the covariates are provided in Appendix D. Values for each of the covariates were attributed to the fish survey sites, as well as a set of model prediction points that were created at 250 m intervals throughout the habitat networks. In addition to the spatial covariates, we also calculated two covariates to account for potential nuisance variation, a categorical variable called "DataSource" in which the levels represented the different agencies that contributed data, and a year effect variable that was represented by the species-specific average annual juvenile densities for the years in the dataset from 2000 through 2018. The final datasets that included the linear fish density observations and covariate values at the observation and prediction points were processed in ArcGIS version 10.3 (ESRI 2014) using STARS version 2.0.4 (downloaded from the SSN/STARS website: www.fs.fed.us/rm/boise/AWAE/projects/SpatialStreamNetworks.shtml), to generate the spatial, topological, and attribute information files needed for spatial model fits with the SSN package (Ver Hoef et al. 2014). These files are provided as ".ssn" directory files as a project deliverable to facilitate replication of our analysis or future reanalyses.

SSN models

Prior to model fitting, fish density values were $\log_{10}$ transformed and covariate values were standardized by subtracting their mean and dividing by their standard deviation to improve computational efficiency during model fits. Pairwise correlations among the covariates were calculated and one member of each pair was removed if strong correlations were observed (e.g., $r > 0.7$) to reduce the potential for multicollinearity to adversely affect model estimates. We also plotted the fish density values versus the covariates to look for nonlinear relationships and added quadratic terms for some covariates where appropriate. After initial data preparation and screening, the number of potential model covariates for both species remained large, so initial model fits were performed in SAS using a non-spatial, best subsets multiple regression procedure to identify the subsets of covariates that were most likely to be statistically significant in the SSN models. Those covariate subsets were used to specify initial models for each species using the SSN package in the R statistical program (Ver Hoef et al. 2014; R Core Team 2018), which then required approximately five days of computation time on a modern workstation to obtain initial fits due to the large size of the datasets. To expedite this process, a new set of statistical code for fitting SSN models was developed that greatly reduced computational requirements, allowing some model fits to be completed in approximately 10 minutes. Details associated with the new code and a complimentary R package for SSN model applications to big data will be described in a future publication (Ver Hoef et al., in preparation). After initial SSN model fits were obtained, non-significant covariates were dropped from the models, which were again refit to arrive at final models for both species.

The final models were used to create prediction maps of juvenile Chinook salmon and steelhead densities throughout the potential habitat networks by using the universal kriging equations (Cressie 1993) to describe 24 different scenarios. The scenarios included a baseline composite scenario of average juvenile densities observed during the 19 year period of 2000-2018 (Scenario 1), annual density scenarios for each year from 2000 through 2018 (Scenarios 2–20), a scenario of the prediction standard errors that represented the spatial precision of the density predictions (Scenario 21), and three future density scenarios associated with the effects of increases in mean August stream temperature of 1°C, 2°C, and 3°C (Scenarios 22–24; Appendix E). The latter three scenarios were developed based on the final SSN model relationships between juvenile densities and mean August stream temperature for each species. To illustrate the utility of the scenarios in subsequent analyses, a simple climate change sensitivity analysis was done by subtracting the predicted juvenile densities in Scenario 23 from those in the baseline Scenario 1 and mapping predicted changes in densities. We also calculated population estimates for the two species by the designated population areas under both scenarios to provide information about the relative sizes of the populations and their potential future trajectories. Population estimates were developed by multiplying the length of potentially suitable habitat within each population area by the average density of juveniles predicted for the areas as described in Isaak et al. (2017a).

Results

Fish datasets

Summaries of the fish density datasets, after linkage to the set of covariate descriptors, are provided in Tables 2 and 3. Chinook salmon surveys spanned a wide range of environmental conditions within the potential habitat network and were available, for example, from streams with mean summer flows (variable name: MS_Hist in Table 2) of 0.01-2,710 cfs, August temperatures (NorWeST_S1) of 6.8-21.6 °C, and reach slopes of 0.01-21.0%. Spatial variation in juvenile Chinook salmon densities among sites ranged from 0 fish/100 m to 5,227 fish/100 m (CH_Density). Temporal variation in annual average densities (YearAveCHDens) during the

Table 2. Descriptive statistics for juvenile Chinook salmon density observations and covariates in the dataset used to develop SSN models.

Variable[a]	*n*	Mean	Median	SD	Minimum	Maximum
MS_Hist (cfs)	2,307	140	52.3	271	0.01	2710
W95_Hist (days)	2,307	2.57	1.76	2.85	0.00	12.7
BFI (%)	2,307	70.0	71.0	6.28	48.0	84.0
NorWest_S1 (°C)	2,307	13.4	13.3	2.20	6.83	21.6
AvgConduct (µS/cm)	2,307	91.5	67.7	57.7	26.5	412.8
Slope (%)	2,307	1.94	1.34	1.90	0.01	21.0
S_Slope (%)	2,307	1.99	1.27	2.15	0.01	19.2
WCF_USFS_Rate	2,182[b]	1.53	1.00	0.59	1.00	3.00
WCF_AQHAB_Rate	2,182	1.69	1.00	0.81	1.00	3.00
WCF_RDTRL_Rate	2,182	2.11	2.00	0.78	1.00	3.00
CarbResid (%)	2,307	1.00	0.00	4.72	0.00	90.3
AlkIntru (%)	2,307	0.00	0.00	0.00	0.00	0.00
ExtruVol (%)	2,307	0.00	0.00	0.00	0.00	0.00
Shrb2011 (%)	2,307	17.2	15.3	10.1	0.00	58.1
Grs2011 (%)	2,307	12.5	9.14	11.5	0.00	66.5
Hay2011 (%)	2,307	0.580	0.000	3.14	0.00	51.6
Crop2011 (%)	2,307	0.595	0.000	4.14	0.00	66.4
Conif2011 (%)	2,307	67.4	70.7	21.3	0.00	99.5
Canopy (%)	2,307	32.2	30.2	19.0	0.00	85.0
Chin_Rate	1,564	1.63	2.00	1.17	0.00	3.00
RdDens (km/km^2)	2,307	0.725	0.540	0.710	0.00	9.15
RdCrsWs (crossings/km^2)	2,307	0.152	0.130	0.141	0.00	1.21
RdDensRp (km/km^2)	2,307	0.821	0.692	0.751	0.00	10.35
BRK_Dens (fish / HUC12 km^2)	2,307	0.086	0.012	0.142	0.00	0.72
SMTH_Pred (occurrence probability)	2,307	0.83	0.55	0.102	0.00	0.97
YearAveCHDens (fish / 100 m)	19	73.3	60.2	49.5	12.8	201
CH_Density (fish / 100 m)	6,757	73.3	5.21	215.9	0.00	5,227

[a]See Appendix D for full variable names and definitions.
[b]Covariate information was not available at all fish survey sites.

Table 3. Descriptive statistics for juvenile steelhead density observations and covariates in the dataset used to develop SSN models.

Variable[a]	*n*	Mean	Median	SD	Minimum	Maximum
MS_Hist (cfs)	2,797	128	42.9	260	0.01	2710
W95_Hist (days)	2,797	2.88	1.93	3.20	0.00	13.4
BFI (%)	2,797	69.7	70.0	6.83	45.0	84.0
NorWest_S1 (°C)	2,797	13.3	13.2	2.25	6.83	21.6
AvgConduct (µS/cm)	2,797	98.3	70.4	64.5	26.5	530
Slope (%)	2,797	2.17	1.49	2.19	0.00	24.1
S_Slope (%)	2,797	2.16	1.40	2.34	0.00	25.8
WCF_USFS_Rate	2,631[b]	1.52	1.00	0.59	1.00	3.00
WCF_AQHAB_Rate	2,631	1.70	1.00	0.81	1.00	3.00
WCF_RDTRL_Rate	2,631	2.13	2.00	0.78	1.00	3.00
CarbResid (%)	2,797	0.99	0.00	4.47	0.00	74.1
AlkIntru (%)	2,797	0.00	0.00	0.00	0.00	0.00
ExtruVol (%)	2,797	0.00	0.00	0.00	0.00	0.00
Shrb2011 (%)	2,797	17.4	15.5	10.5	0.00	97.8
Grs2011 (%)	2,797	12.6	8.88	11.9	0.00	80.9
Hay2011 (%)	2,797	0.48	0.00	2.83	0.00	51.6
Crop2011 (%)	2,797	0.70	0.00	4.62	0.00	77.3
Conif2011 (%)	2,797	67.0	70.0	21.1	0.00	99.9
Canopy (%)	2,797	32.5	30.5	19.2	0.00	87.6
STHD_Rate	2,768	2.16	1.40	2.34	0.00	25.8
RdDens (km/km^2)	2,797	0.765	0.597	0.726	0.00	9.15
RdCrsWs (crossings/km^2)	2,797	0.161	0.133	0.159	0.00	2.94
RdDensRp (km/km^2)	2,797	0.860	0.718	0.765	0.00	10.4
BRK_Dens (fish / HUC12 km^2)	2,797	0.080	0.010	0.138	0.00	0.717
SMTH_Pred (occurrence probability)	2,797	0.085	0.055	0.104	0.00	0.967
YearAveOMDens (fish / 100 m)	19	26.6	27.4	9.34	9.50	43.0
OM_Density (fish / 100 m)	7,436	26.6	7.51	52.3	0.00	826

[a]See Appendix D for full variable names and definitions.
[b]Covariate information was not available at all fish survey sites.

period 2000–2018 ranged from a low of 12.8 fish/100 m in 2000 to 201 fish/100 m in 2003. Steelhead density surveys spanned a similarly wide range of environmental conditions within their potential habitat network (Table 3) but variation in densities among sites ranged from 0 fish/100 m to 826 fish/100 m (OM_Density in Table 3). Temporal variation in annual average densities (YearAveOMDens) during the period 2000–2018 ranged from a low of 9.5 fish/100 m in 2000 to 43 fish/100 m in 2003.

For both species, empirical Torgegrams were calculated from the density datasets using the SSN software to check for the presence of spatial autocorrelation. Autocorrelation was apparent in both datasets, as indicated by patterns of increasing semivariance values as the distances separating observations increased (Figure 3). These patterns were expected due to the spatial clustering among density observation (Figure 1), but confirmed that SSN models were appropriate for application to these datasets.

SSN model performance

The final model for Chinook salmon explained 57% of the variation in juvenile densities (Figure 4a) and included seven statistically significant covariates (Table 4). Two of the covariates had linear effects, whereas the remaining five covariates had quadratic effects. An earlier model fit also suggested the DataSource variable was significant but it was dropped from the final model because it caused errors during attempts to create prediction scenarios. Figure 5 shows response curves describing the relationships between significant covariates and juvenile Chinook salmon density in the final model. The range of densities spanned on the Y-axes in the curves provides some measure of the relative importance of the covariates. The largest density effects were associated with inter-annual variation in average densities, reach slope, August temperature, and mean summer flow; whereas smaller density effects were associated with brook trout density, riparian canopy density, and baseflow index values. Viewed collectively, the model predicted that densities of juvenile Chinook salmon were greatest in low slope reaches (e.g., < 2%) with cold August temperatures (e.g., 14-17°C), intermediate summer flows (e.g., 200-1,000 cfs), intermediate canopy densities (e.g., 20-50%), intermediate baseflows (e.g., 65-75%), and higher densities of brook trout.

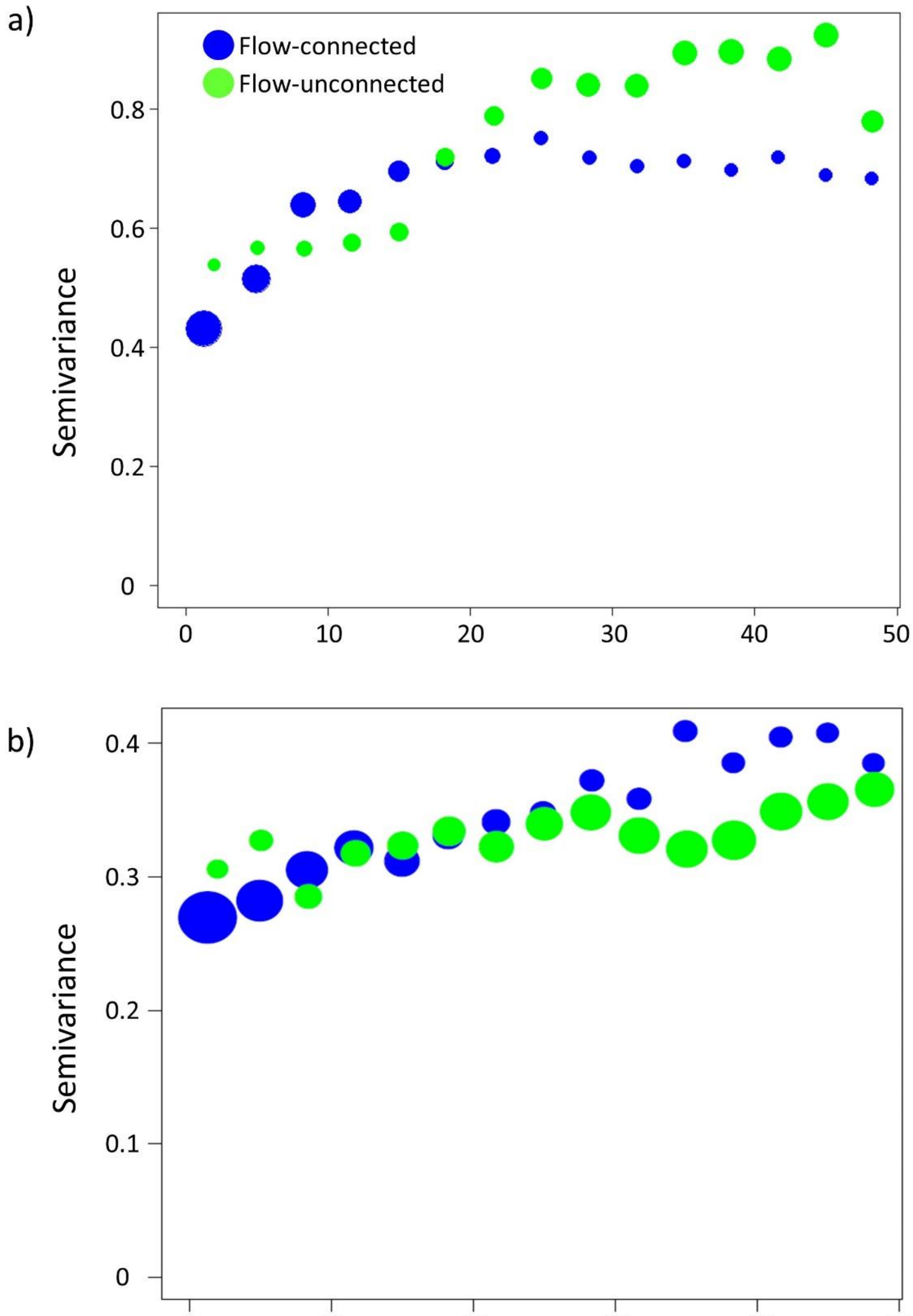

Figure 3. Empirical Torgegrams describing patterns in spatial similarity among juvenile density datasets for Chinook salmon (a) and steelhead (b). Symbol sizes are proportional to the number of data pairs averaged for each semivariance value. The trends of increasing semivariances with stream distance shown in each plot indicates that the density samples are spatially correlated and SSN models were appropriate for the analysis.

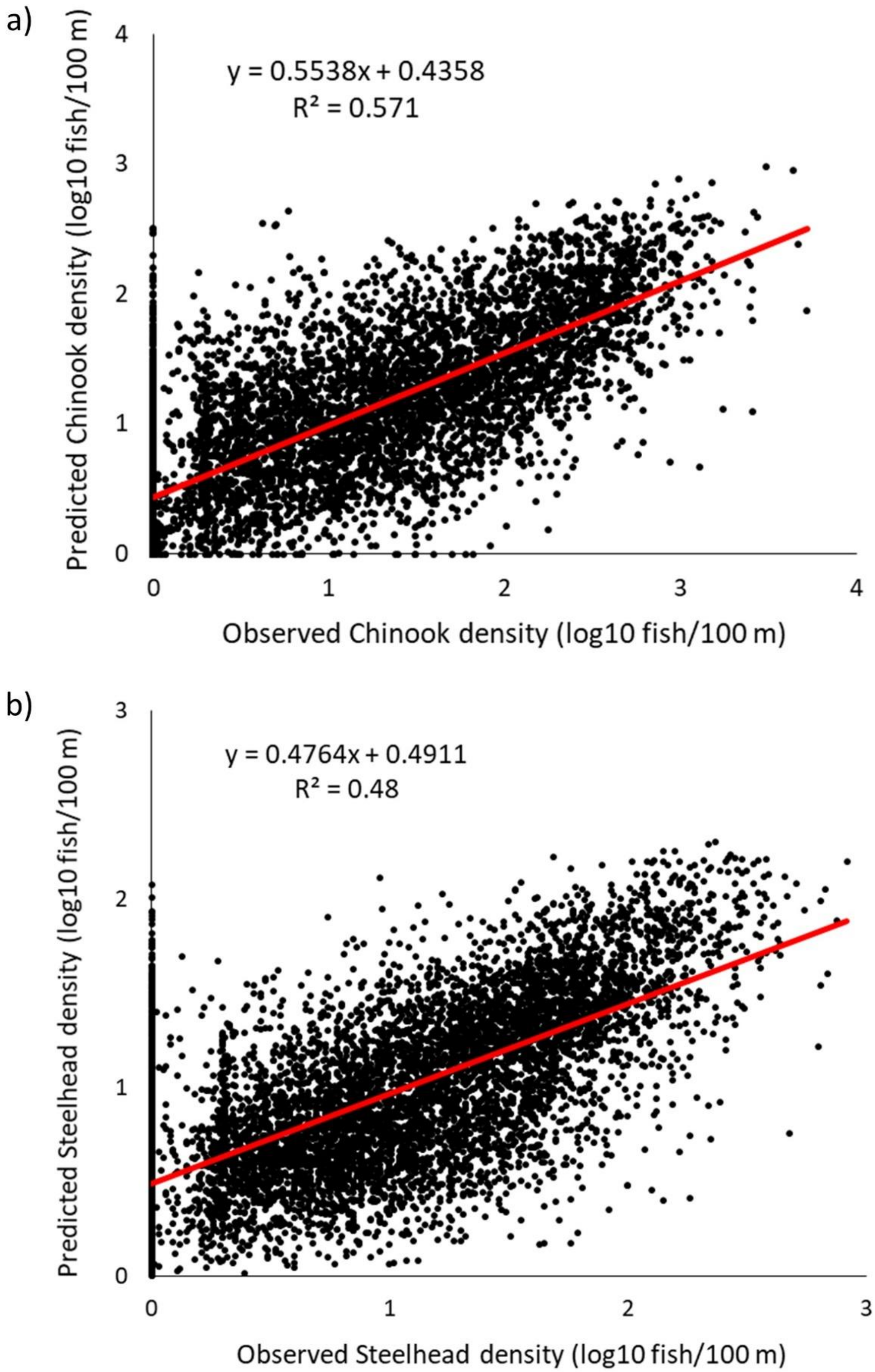

Figure 4. Correlations between SSN model leave-one-out cross-validation predictions of juvenile fish densities and observed values for Chinook salmon (a; n = 6,757) and steelhead (b; n = 7,436). Note that plotted values are on a logarithmic scale.

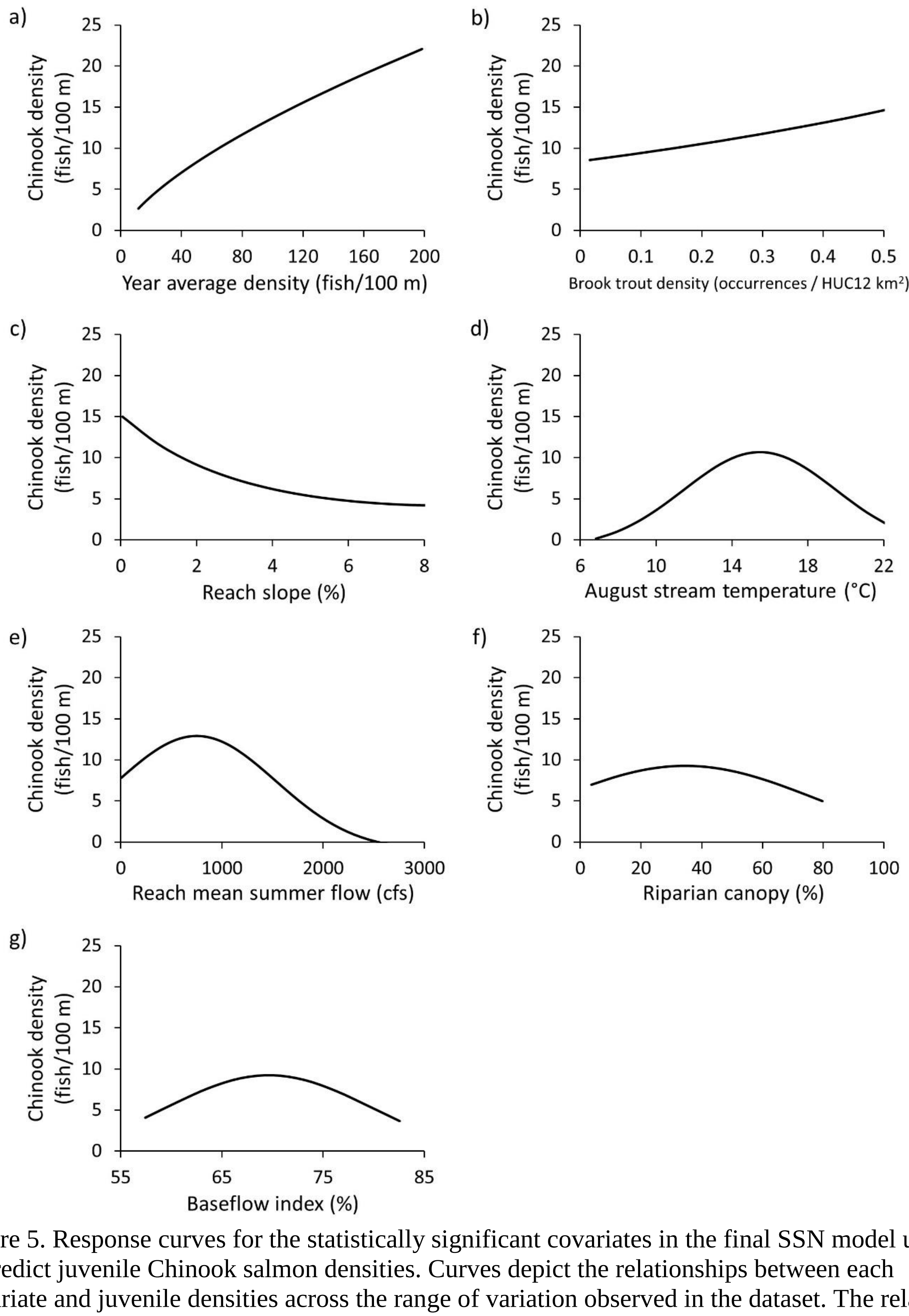

Figure 5. Response curves for the statistically significant covariates in the final SSN model used to predict juvenile Chinook salmon densities. Curves depict the relationships between each covariate and juvenile densities across the range of variation observed in the dataset. The relative importance of the covariates can be inferred by the size range of densities on the Y-axes.

Table 4. Summary statistics for the statistically significant covariates in the final SSN models that predict juvenile Chinook salmon densities within the project area. Note that covariates were standardized prior to analysis and often included quadratic effects, so the response curves in Figure 5 are useful for interpreting relationships with fish densities.

Covariates	*b* (SE)	t value	p-value	CV r^2 [a]
Intercept	-0.165 (0.0748)	-2.201	0.0278	0.57
YearAveCHD	0.664 (0.0261)	25.5	< 0.001	
BRK_Dens	0.0627 (0.0303)	2.07	0.038	
Slope	-0.168 (0.029)	-5.80	< 0.001	
$Slope^2$	0.0239 (0.0064)	3.71	< 0.001	
AugustTemp	0.121 (0.0339)	3.57	< 0.001	
$AugustTemp^2$	-0.0654 (0.0154)	-4.24	< 0.001	
MS_Hist	0.118 (0.0568)	2.07	0.039	
MS_Hist^2	-0.0261 (0.0084)	-3.12	0.002	
Canopy	0.0104 (0.0173)	0.60	0.549	
$Canopy^2$	-0.0414 (0.0119)	-3.49	< 0.001	
BFI	-0.00929 (0.0583)	-0.159	0.873	
BFI^2	-0.0811 (0.0272)	-2.98	0.003	

[a]Squared correlation between the leave-one-out cross-validation prediction and observed juvenile Chinook salmon.

The final steelhead model included almost the same set of covariates as the Chinook salmon model, except that the baseflow variable was not significant and the Conif2011 (watershed area covered by conifers) variable was significant (Table 5). Another difference was the nature of the relationships between the covariates and steelhead densities as depicted by the model response curves (Figure 6). Steelhead densities, for example, were negatively affected by higher brook trout densities and were highest in reaches with intermediate slopes (e.g., 4-8%), warmer August temperatures (e.g., 16-20°C), and smaller summer flows (e.g., < 500 cfs). An earlier model fit also suggested the DataSource variable was statistically significant but it was again excluded from the final model due to errors it caused in prediction scenarios.

Juvenile density scenarios

Maps depicting the predicted densities from the final models for both species in the Scenario 1 baseline are shown in Figure 7. Stream reaches with high densities of juvenile Chinook salmon were patchily distributed throughout the project area, which contrasts with steelhead densities that showed a westerly gradient toward increasing densities. The latter gradient is probably due to the warmer thermal niche of steelhead juveniles and streams in the western portion of the study area being warmer, on average, than those in central Idaho.

Figure 8 maps the predicted densities of Chinook salmon for Scenario 23 associated with a 2°C increase in mean August stream temperature. The spatial distribution of high density areas appears similar to the Scenario 1 baseline but subtle changes are apparent when the differences between the scenarios are mapped (Figure 8a). The difference map suggests juvenile Chinook salmon densities will increase in many cold streams throughout the Salmon River basin while decreasing in warmer, lower elevation Clearwater River basin streams and significant portions of Oregon. However, local anomalies marked by density increases are also apparent in those areas. For example, higher densities are predicted to occur in especially cold streams within the Grande Ronde basin such as the Minam River, Lookingglass Creek, and upstream reaches of the Grande Ronde River. These differential effects of temperature increases are predicted because of the nonlinear stream temperature relationship in the final model, which suggests peak juvenile Chinook densities occur at ~15°C (Figure 5). In stream reaches colder than that temperature, therefore, temperature increases are predicted to be beneficial while the opposite is true in

Table 5. Summary statistics for the statistically significant covariates in the final SSN models that predict juvenile steelhead densities within the project area. Note that covariates were standardized prior to analysis and often included quadratic effects, so the response curves in Figure 6 are useful for interpreting relationships with fish densities.

Covariates	*b* (SE)	t value	p-value	CV r^{2} [a]
Intercept	0.133 (0.0877)	1.51	0.13	0.48
YearAveOMD	0.604 (0.0373)	16.2	< 0.001	
BRK_Dens	-0.204 (0.0549)	-3.72	< 0.001	
BRK_Dens^2	0.0520 (0.0173)	3.01	0.003	
Slope	0.0791 (0.0228)	3.47	< 0.001	
$Slope^2$	-0.0179 (0.00435)	-4.12	< 0.001	
AugustTemp	0.207 (0.0276)	7.50	< 0.001	
$AugustTemp^2$	-0.0498 (0.0131)	-3.82	< 0.001	
MS_Hist	-0.123 (0.0213)	-5.76	< 0.001	
Canopy	0.0396 (0.0137)	2.90	0.004	
$Canopy^2$	-0.0217 (0.00905)	-2.39	0.0168	
Conif2011	0.0696 (0.030)	2.32	< 0.001	

[a]Squared correlation between the leave-one-out cross-validation prediction and observed juvenile steelhead densities.

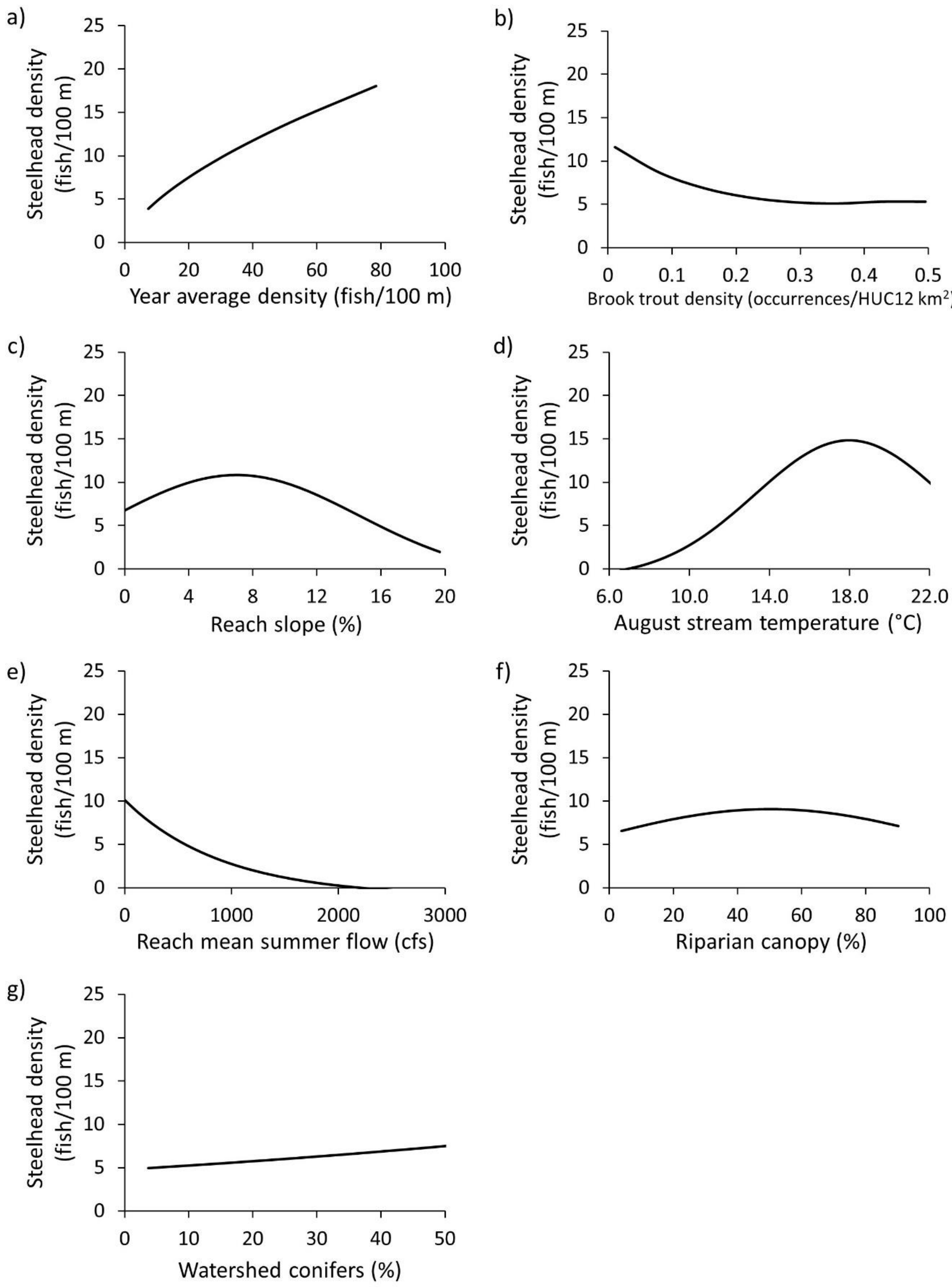

Figure 6. Response curves for the statistically significant covariates in the final SSN model used to predict juvenile steelhead densities. Curves depict the relationship between each covariate and juvenile densities across the range of variation observed in the dataset. The relative importance of the covariates can be inferred by the size range of densities on the Y-axes.

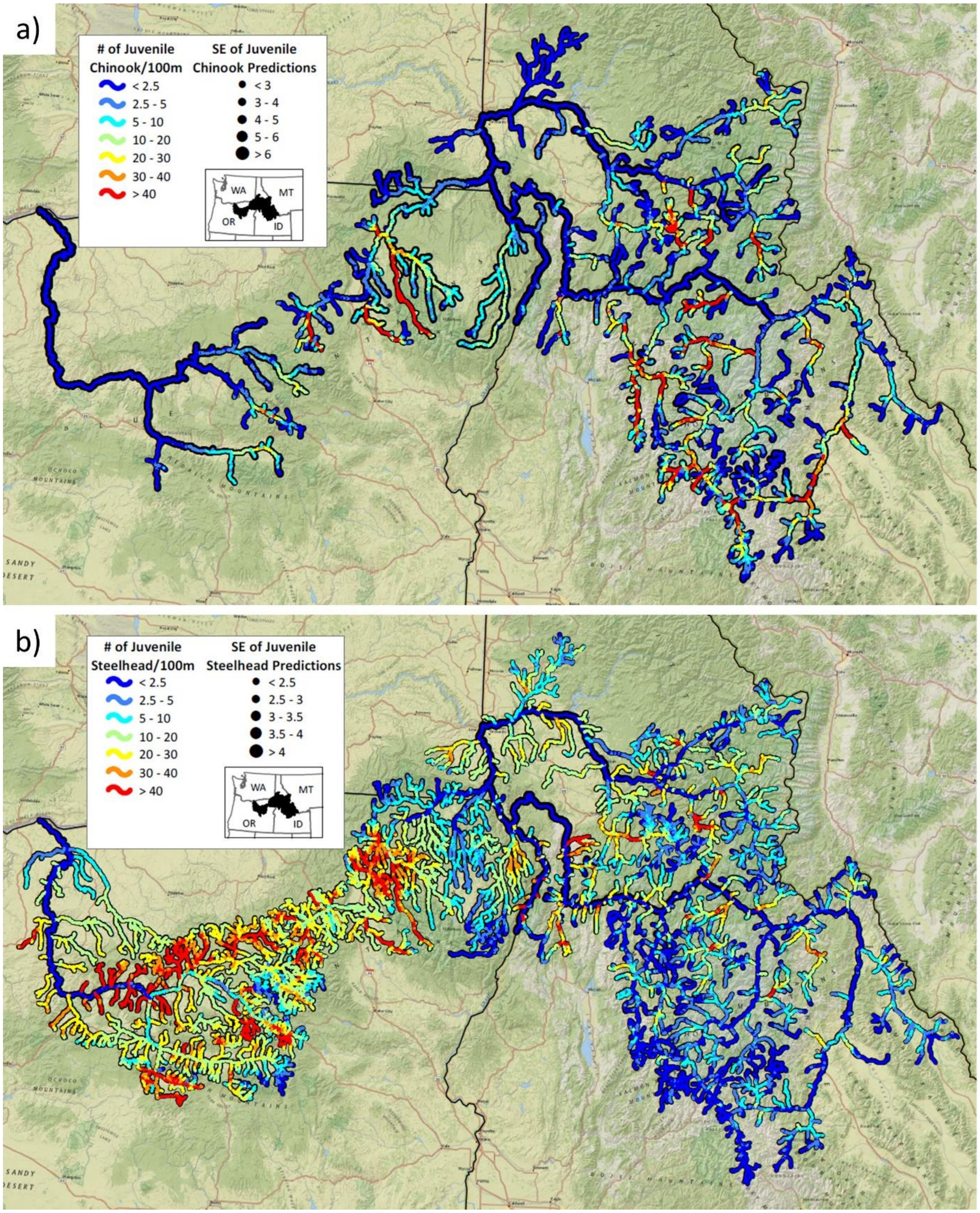

Figure 7. Scenarios for the potential habitat networks of juvenile Chinook salmon (a) and steelhead (b) predicted from the final SSN models. In each panel, Scenario 1 values are represented as the colored reaches and depict the average density of juvenile fish for the period of 2000-2018. Also in each panel, Scenario 21 values are shown as the width of the black margin that borders individual reaches and represent the standard errors of the density predictions. Fish density values in these scenarios and many others are summarized in ArcGIS shapefiles delivered as part of this report.

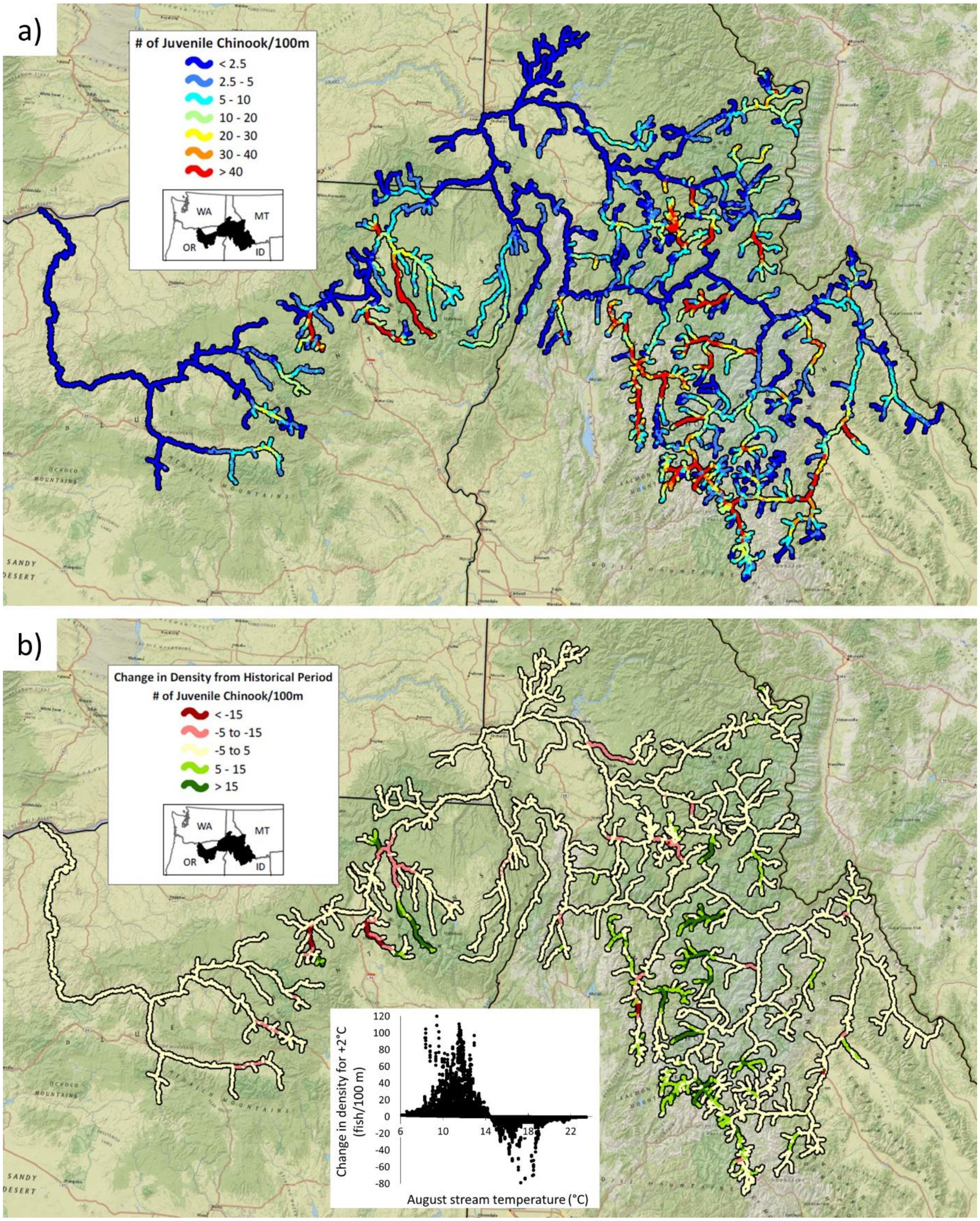

Figure 8. Scenario 23 that depicts predicted juvenile Chinook salmon densities associated with a 2 °C increase in mean August stream temperatures that could occur by late century (a). Differences in density values between Scenario 23 and the baseline densities of Scenario 1 shown in Figure 7a highlight the spatial diversity of responses that are predicted (b). Inset graph in panel b indicates that future density changes differ along a spatial gradient of thermal conditions, with increases expected in streams colder than 14°C and decreases expected in warmer streams.

streams that are currently warmer than 15°C (Figure 8b inset). For steelhead, Figure 9 depicts the same Scenario 23 density map and differences compared to Scenario 1 baseline conditions. Because steelhead have a warmer thermal niche than Chinook salmon, however, a temperature increase of 2°C is predicted to increase their densities in most streams throughout the project area (Figure 9b). The only exceptions appear to be especially warm portions of the middle Grande Ronde River and downstream portions of a few small tributaries in the John Day basin.

The information from the previous scenarios can also be summarized by discrete geographic areas to provide population estimates at different scales. Tables 6 and 7 summarize the total abundance of juveniles for each of the NOAA designated population areas under Scenarios 1 and 23. The estimates for Chinook salmon range from 771 total juveniles in the Asotin Creek population, which has low average predicted densities and predicted habitat length, to 79,735 juveniles for the much larger South Fork Salmon River population area. As was the case in the previous reach-scale analysis of a 2°C increase (Figure 8b), predicted effects at the population scale were variable (Table 6). Total population size was predicted to increase in 23 of the 35 population areas while decreasing in 12 of the population areas. Population scale summaries for steelhead show higher overall population estimates (Table 7) compared to Chinook salmon, primarily because their potential habitat networks in the population area boundaries are much larger. As would be expected, given the relatively warm thermal niche of steelhead, the changes in population sizes predicted to occur in Scenario 23 under a 2°C change were all increases.

Discussion

The compilation of large juvenile salmonid density datasets, and their use with SSN models provided robust fits, numerous insights, and several data products for the target species. The predictive accuracy of the SSN models matched or exceeded that observed with smaller datasets in the Phase 1 pilot project and in a separate application to trout electrofishing survey data (Isaak et al. 2017a; Peterson et al. 2018). This was surprising given differences among the agency datasets used for this report but highlights the power of using large datasets and consistent sets of geospatial covariates to represent environmental conditions across a diverse area. Just as importantly, the final SSN models for Chinook salmon and steelhead were ecologically realistic

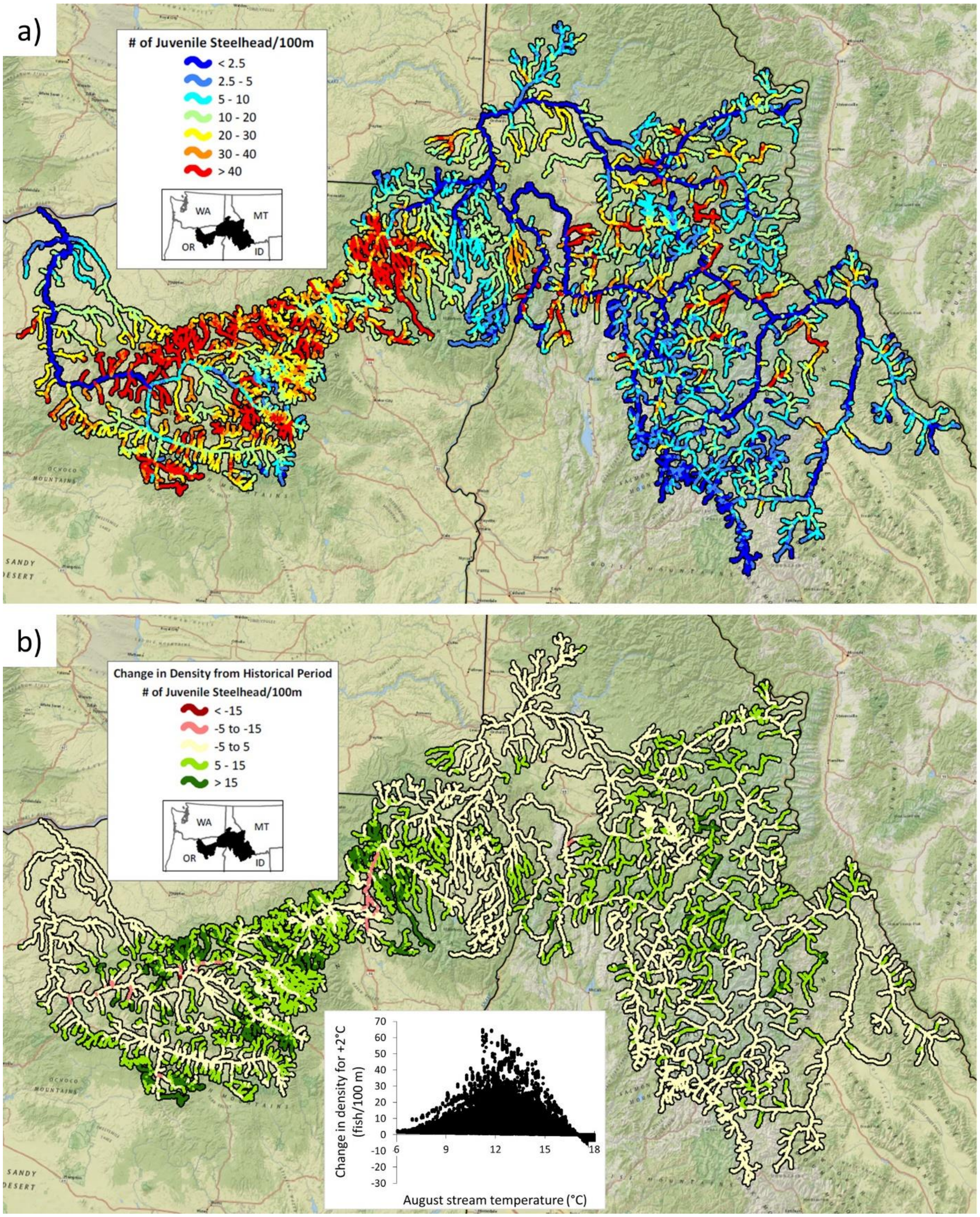

Figure 9. Scenario 23 that depicts predicted juvenile steelhead densities associated with a 2 °C increase in mean August stream temperatures that could occur by late century (a). Differences in density values between Scenario 23 and the baseline densities of Scenario 1 shown in Figure 7b highlight the spatial diversity of responses that are predicted (b). Inset graph in panel b indicates that future density changes differ along a spatial gradient of thermal conditions, with increases expected in streams colder than 17°C and decreases expected in warmer streams.

Table 6. Population estimates and average densities of juvenile Chinook salmon for 35 population areas in the Scenario 1 baseline scenario and a scenario representing the effects of a 2 °C increase in August stream temperatures (Scenario 23).

Population area name	Habitat network length (km)	Scenario 1 average density (fish / 100 m)	Scenario 1 population estimate	Scenario 23 average density (fish / 100 m)	Scenario 23 population estimate	Change in population size
Asotin Creek	57.8	1.33	771	1.16	670	-101
Bear Valley Creek	149	30.15	44,838	36.96	54,979	10,141
Big Creek	186	24.62	45,827	33.52	62,385	16,558
Big Sheep Creek	79.2	7.29	5,773	6.36	5,035	-737
Camas Creek	138	3.54	4,896	4.98	6,890	1,994
Catherine Creek	214	36.72	78,441	29.19	62,357	-16,083
Chamberlain Creek	241	25.68	61,788	36.30	87,350	25,562
East Fork Salmon River	151	9.37	14,136	12.23	18,442	4,306
East Fork South Fork Salmon River	174	25.87	44,929	33.81	58,726	13,796
Grande Ronde R. Upper Mainstem	274	15.67	42,907	14.48	39,666	-3,241
Imnaha River Mainstem	163	9.19	14,954	7.67	12,484	-2,470
Lemhi River	233	4.17	9,714	4.61	10,726	1,012
Little Salmon River	238	6.93	16,481	6.90	16,410	-71
Lookingglass Creek	38.2	25.83	9,862	38.80	14,812	4,950
Loon Creek	112	9.28	10,368	13.88	15,508	5,141
Marsh Creek	113	32.90	37,203	56.56	63,961	26,758
Middle Fork John Day	215	5.75	12,358	4.24	9,124	-3,234
Middle FK Salmon R. Lower Mainstem	187	5.10	9,518	4.90	9,142	-376
Middle FK Salmon R. Upper Mainstem	248	12.00	29,730	16.07	39,811	10,081
Minam River	91.5	85.36	78,135	103.71	94,924	16,789
North Fork John Day	316	4.34	13,736	3.52	11,131	-2,605
North Fork Salmon River	170	5.78	9,845	6.67	11,363	1,518
Pahsimeroi River	46.7	37.19	17,373	41.79	19,518	2,145
Panther Creek	120	13.13	15,819	14.95	18,010	2,191
Salmon River Lower Mainstem	377	20.45	77,072	20.55	77,448	375
Salmon River Upper Mainstem	196	17.45	34,228	21.80	42,756	8,528
Secesh River	113	21.98	24,923	29.47	33,414	8,491
Snake River Lower Mainstem	994	3.11	30,888	2.02	20,103	-10,785
South Fork Salmon River	418	19.09	79,735	19.25	80,367	632
Sulphur Creek	29	7.31	2,087	10.78	3,077	990
Upper John Day	193	6.48	12,496	4.93	9,503	-2,992
Valley Creek	109	15.03	16,436	19.92	21,785	5,349
Wallowa/Lostine Rivers	231	12.80	29,543	11.55	26,643	-2,899
Wenaha River	132	2.58	3,394	3.57	4,707	1,313
Yankee Fork	136	3.09	4,214	5.29	7,207	2,993

Table 7. Population estimates and average densities of juvenile steelhead for 29 population areas in the Scenario 1 baseline and a scenario representing the effects of a 2 °C increase in August stream temperatures (Scenario 23).

Population area name	Habitat network length (km)	Scenario 1 average density (fish / 100 m)	Scenario 1 population estimate	Scenario 23 average density (fish / 100 m)	Scenario 23 population estimate	Change in population size
Asotin Creek	247	14.9	36,782	17.9	44,203	7,421
Chamberlain Creek	718	11.7	84,173	18.0	129,337	45,164
Clearwater River Lower Mainstem	970	11.4	111,027	12.4	120,430	9,403
East Fork Salmon River	282	4.7	13,178	7.2	20,382	7,204
Grande Ronde River Lower Mainstem	634	7.7	48,989	11.1	70,316	21,327
Grande Ronde River Upper Mainstem	1,550	30.0	464,447	38.3	593,321	128,874
Imnaha River	573	10.3	59,036	12.8	73,351	14,316
John Day R. Lower Mainstem Tributaries	1,716	19.6	335,978	21.6	369,811	33,833
John Day River Upper Mainstem	693	18.6	128,878	23.2	160,677	31,800
Joseph Creek	444	6.2	27,610	7.9	35,096	7,486
Lemhi River	394	4.5	17,681	7.4	29,067	11,386
Little Salmon River	491	16.3	80,112	21.4	105,361	25,248
Lochsa River	604	8.8	53,181	13.2	79,386	26,205
Lolo Creek	126	5.1	6,458	6.3	7,961	1,503
Middle Fork John Day River	646	28.9	186,523	36.5	236,007	49,484
Middle FK Salmon R. Lower Mainstem	778	6.7	52,345	11.7	91,048	38,703
Middle FK Salmon R. Upper Mainstem	769	3.1	23,527	5.9	45,387	21,860
North Fork John Day River	1,654	27.4	452,921	34.7	574,250	121,329
North Fork Salmon River	228	5.9	13,370	10.6	24,161	10,791
Pahsimeroi River	161	4.0	6,465	5.7	9,237	2,772
Panther Creek	301	11.6	34,845	18.1	54,406	19,561
Powder River	225	9.2	20,705	11.2	25,273	4,568
Salmon River Upper Mainstem	582	3.2	18,529	6.1	35,380	16,851
Secesh River	164	4.8	7,804	8.1	13,225	5,421
Selway River	888	12.1	107,446	17.5	155,230	47,784
South Fork Clearwater River	630	10.2	64,090	13.7	86,506	22,417
South Fork John Day River	274	44.7	122,604	58.0	159,105	36,501
South Fork Salmon River	730	4.0	29,270	7.0	51,225	21,955
Wallowa River	555	25.2	140,020	34.3	189,941	49,921

and reflected habitat preferences and density patterns that are widely acknowledged by biologists and documented in the literature (Montgomery et al. 1999; Burnett et al. 2007). Dominant covariates in both models were related to gradients in proximal stream characteristics such as reach slope, stream size, riparian density, and temperature, with few effects discerned for more diffuse watershed factors associated with land-use, land-cover, or geologic type.

The models did not detect an effect of road density on juvenile fish densities despite the well-recognized negative effects of this factor on many salmonid species (Meehan 1991; Roni et al. 2002). This highlights a few important considerations and caveats on the analysis. First, the ability of the SSN models to test covariate effects is only as good as the accuracy of the geospatial datasets that quantify these effects within the project area. Some of the covariates used in the analysis are relatively coarse and derived from national datasets based on sparse underlying measurements whereas others are precise and derived from dense measurements and spatial interpolation routines that are tuned to conditions in the Pacific Northwest. Second, releases of hatchery fish may alter patterns in spatial densities from those exhibited by wild fish. Because it is impossible to separate hatchery and wild fish in the analysis datasets, covariate assessments and the relationships described by model response curves are likely to be affected to some degree. Third, much of what is known about salmonid ecology is based on studies using small datasets collected at small spatial scales. In that context, the importance of some covariates may be overestimated and consideration of patterns and inferences that emerge from larger datasets and geographic perspectives can provide important balance.

Those factors aside, the accuracy of the final models and their ecological realism suggests the prediction scenarios provide useful information about spatial patterns of abundance throughout the project area. Moreover, the scenario density information is available as ArcGIS shapefiles at a 250-m resolution throughout the thousands of kilometers that constitute the potential habitat networks to provide considerable flexibility in subsequent analyses and data summaries. For illustrative purposes, the baseline densities represented by Scenario 1 were used to provide a status assessment and summarize population sizes among NOAA designated population areas. The example was extended to a climate sensitivity analysis by calculating the difference between the baseline scenario and one representing the effects of a plausible late-century 2°C temperature increase (Isaak et al. 2018). Differences revealed that temperature increases could benefit juvenile densities in many places but also highlighted reaches where populations may be at risk of declines. This strategic information could be coupled with more precise local models and information about habitat conditions and population status to help inform restoration investments (Nichols et al. 2013; Justice et al. 2017).

The size of the fish survey datasets compiled for this report, further enhanced by the application of a consistent analysis format, makes them a valuable resource. The observation datasets are available as ArcGIS shapefiles that can be queried to show where redundancies exist among agencies, which sites have the most consistent long-term monitoring records, and potentially to consider how future monitoring might be allocated for improved efficiency and achievement of conservation goals. Although data from partner agencies were successfully integrated to an analysis dataset, the statistical significance of the "DataSource" covariate in preliminary models indicated that systematic differences among agencies existed. This was not surprising because of the different protocols used in data collection (snorkeling and electrofishing) and processing (single-pass index counts and multiple pass population estimates) prior to its submission to the SSN project. Better standardization within and among partner agencies in collection of future juvenile fish surveys would be beneficial and could enhance subsequent SSN model applications but may also be secondary to the primary considerations that many monitoring programs have given a need to maintain consistency with previous protocols.

Phase 2 of the Spatial Stream Networks for Salmonids project encompassed a large geographic area and sample sizes sufficient to highlight the strengths and limitations of the approach. If deemed useful by BPA, subsequent project phases could be extended to include larger portions of the Columbia River basin or its entirety using the scalable approach described in Phases 1 and 2 of this project. Subsequent phases would benefit from newly improved SSN statistical software that facilitates faster model fits and selection but may not reveal covariate relationships that differ materially from the final models here because of the range of diversity already in the dataset and limited options for additional covariates to assess. The predictive accuracy of the models and associated map scenarios would be expected to remain similar to the accuracies achieved in Phase 2 with the addition of more data from other basins. Extension of the approach would further the organization and standardization of existing multi-agency juvenile fish survey datasets and could also involve implementation of an operational Fish Data Analysis Tool described in the Peterson et al. (2020) companion report. That tool would create an efficient online system for uploading consistently formatted fish density data sets by monitoring partners, facilitate periodic SSN model refits, visualize patterns in fish densities to help inform BiOp strategies and tributary habitat prioritization. Much of the FDAT-SSN analytical architecture could also be readily adapted for applications involving other species and data types (e.g., temperature data, eDNA data) that are frequently collected in stream networks throughout the Columbia River basin.

Adaptive management

The juvenile density observations and SSN prediction scenarios have several potential applications within BPA's Fish and Wildlife Program. The scenarios provide spatially continuous information about densities that provides some measure of local habitat quality, and could be combined with geospatial datasets from other sources that describe habitat degradation or intrinsic potential to identify and prioritize locations where restoration investments are useful. Similarly, the juvenile density scenarios, when combined with information about current and future stream temperatures, can be used to assess spatial variation in thermal risks posed by climate change. Based on the example analysis done in this report, some degree of future temperature increase could have a net beneficial effect on juvenile densities, although populations currently inhabiting especially warm streams may be at risk of decline in some basins. Because of the large amount of local heterogeneity, however, future benefits and risks may vary between populations that inhabit streams in close proximity and the strategic information provided by the density scenarios should be bolstered with more detailed local information when available for decision making.

The scenarios and their underlying fish survey databases may also be useful in guiding future monitoring efforts to reduce current levels of spatial uncertainty. Scenario 21 provides the prediction standard errors from the SSN models, which can be displayed in geospatial software with the juvenile densities at the observation locations to highlight where survey data exist relative to the model's local prediction precision. In areas with sparse data and low model precision, for example, additional density samples would be useful for improving the model and might be obtained simply by redirecting sampling effort from nearby areas with many samples and higher levels of model precision. In the process of creating the juvenile density dataset for SSN modeling, analysts encountered a variety of data formats and survey types that are used by resource agencies across the Columbia River basin. Key information from those disparate data formats was extracted to conduct a successful analysis, and that subset of information could now lay the groundwork to develop and implement a consistent juvenile survey Data Exchange Standard (DES). Operationalization of that DES in concert with a basin-scale and fully functional FDAT tool could prove beneficial by improving the efficiency of annual data archiving, provide timely summarization for reports, and lead to relatively routine SSN analyses and model predictions that continually improve with underlying juvenile density datasets.

Acknowledgements

We extend our thanks to the biologists that contributed fish density survey information for this project—Casey Justice and Seth White with CRITFC, Ed Sedell, Lindsy Ciepiela, and Joseph Feldhaus with ODFW, Kevin Sees and Braden Lott with BioMark, Mary Barczak with USFS, and Evan Brown and Tim Copeland with IDFG.

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Appendix A. Links to additional datasets, tools, protocols, and methods associated with this project.

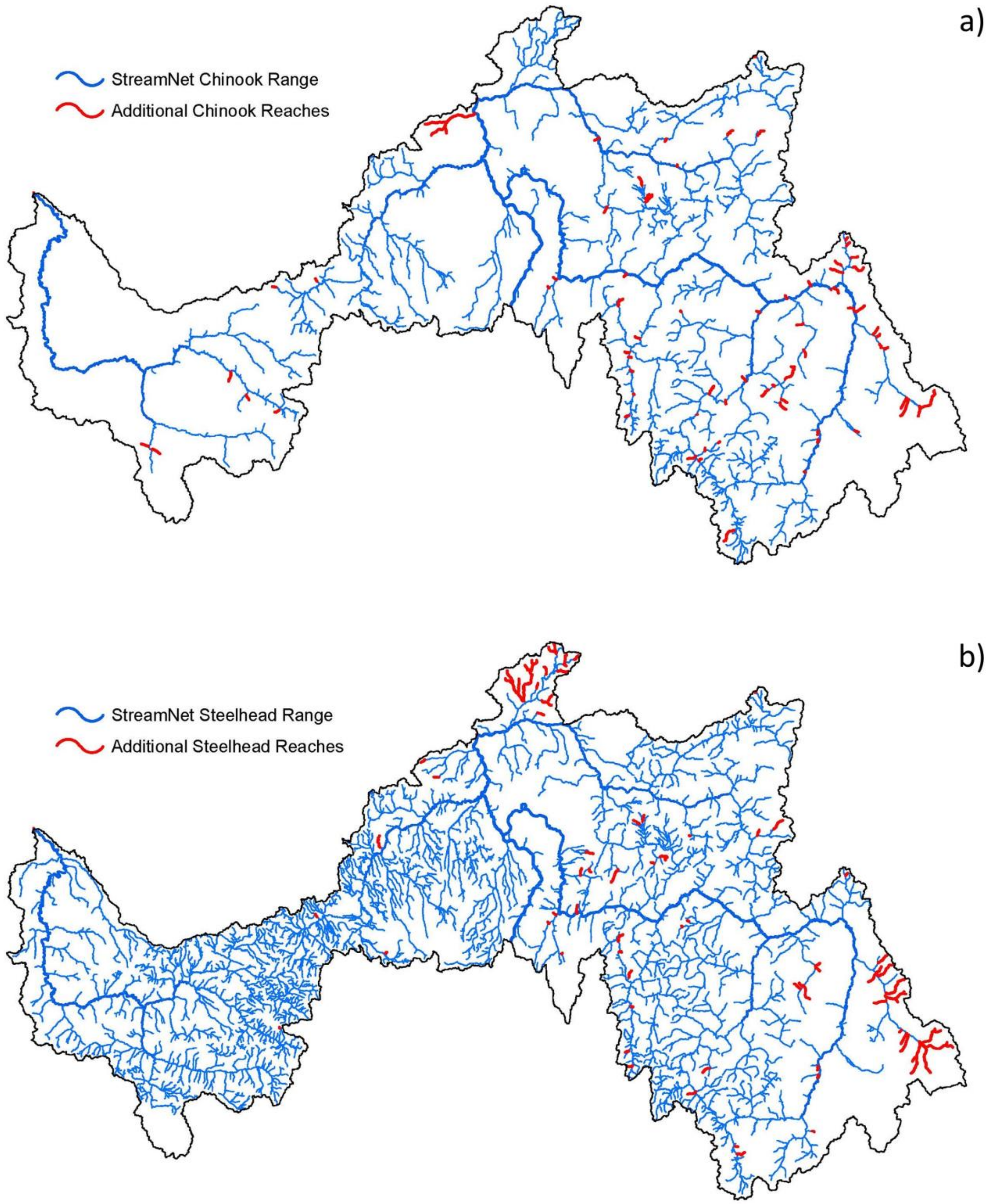
To access the juvenile salmonid GIS datasets, navigate to the StreamNet Datastore https://app.streamnet.org/datastore_search_classic.cfm and search for the "Fish Data Analysis Tools (FDAT) Version 2. 2020."

To access the protocol description for this project in Monitoringresources.org, navigate to https://www.monitoringresources.org/Document/Protocol/Details/3452 and search for "Spatial Stream Networks for Anadromous Fish Abundance and Distribution v2.0"

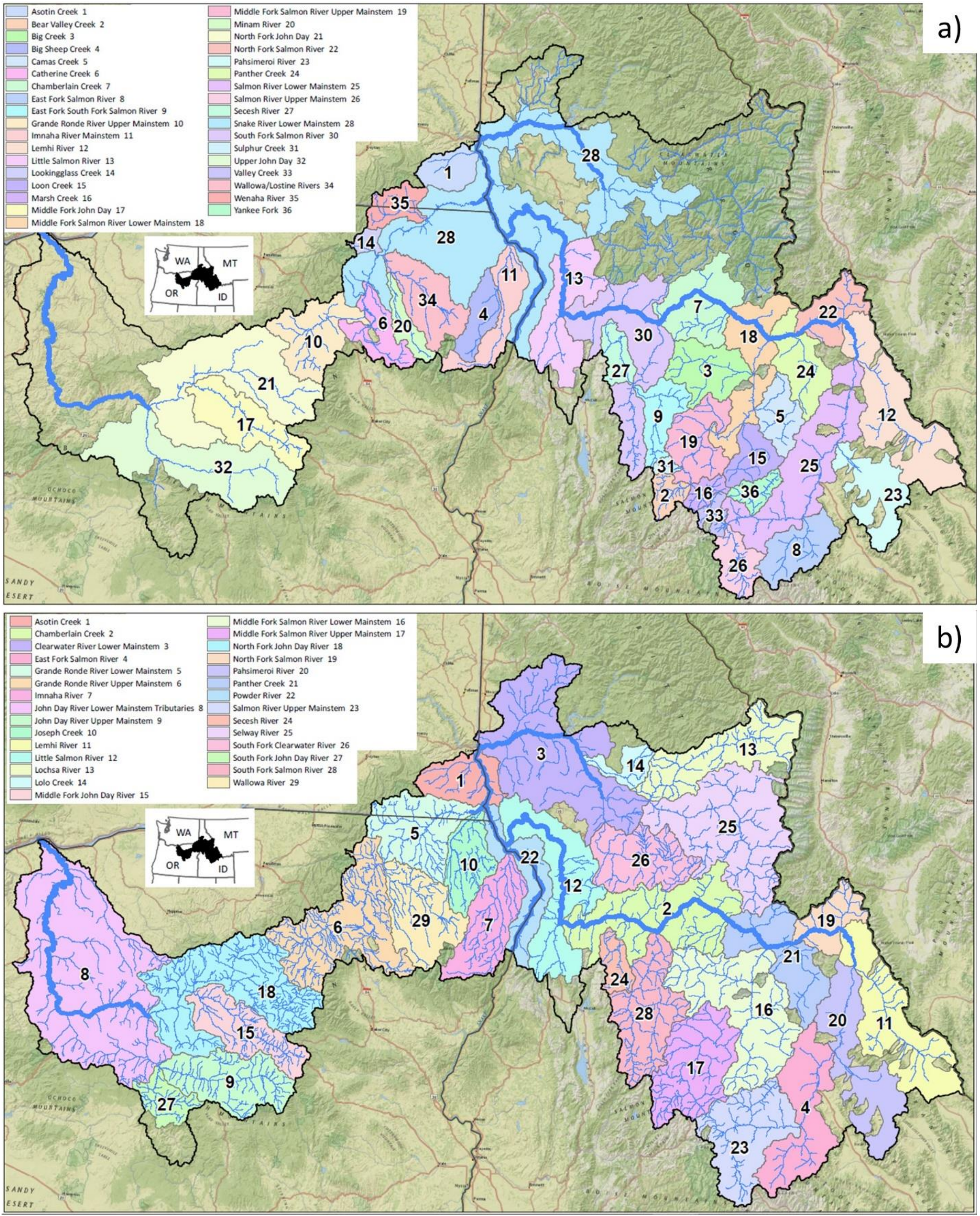
To access the method description for this project in Monitoringresources.org, navigate to https://www.monitoringresources.org/Document/Method/Details/6867 and search for "Method: Spatial Stream Network (SSN) block-krige estimation for salmonid abundance v2.0"

To access the FDAT open source tool set, navigate to GIT HUB (https://github.com/) and follow directions associated with the project protocol https://www.monitoringresources.org/Document/Protocol/Details/3452.

Appendix B. Map showing locations of reaches added to the StreamNet distribution layers for Chinook salmon (a) and steelhead (b) prior to SSN analysis. Reaches were added where fish survey datasets indicated the occurrence of either target species outside the extent of the StreamNet distribution layer. The lengths of reaches added totalled 381 km and 580 km for Chinook salmon and steelhead, respectively.



Appendix C. Designated population areas for Chinook salmon (a) and steelhead (b) used to summarize juvenile densities predicted by SSN models.



Appendix D. Variables used to develop SSN models for predicting juvenile Chinook salmon and steelhead densities across the project area.

Variable and abbreviation	Definition	Data source
Mean summer flow (MS_Hist[a])	Mean summer flow in stream reaches for a historical climate period of 1976-1997. Provides a consistent measure of stream size among reaches in the study area.	Flow value dataset developed by Wenger et al. (2010) for NHDPlus reaches. Downloaded from the Western U.S. Streamflow Metrics website at https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml.
Winter high-flow days (W95_Hist)	The number of days with flows exceeding the 95th percentile during the winter. Provides a measure of hydrologic flashiness that differentiates between stream reaches with snowmelt and rainfall runoff regimes.	Flow value dataset developed by Wenger et al. (2010) for NHDPlus reaches. Downloaded from the Western U.S. Streamflow Metrics website at https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml.
Baseflow Index (BFI)	Base-flow ratio for stream reaches calculated as the ratio of summer low flows to total annual flow and expressed as a percentage. Sites with larger baseflow values have more stable hydrographs and groundwater contributions.	Dataset developed by Wolock (2003) and downloaded from http://ks.water.usgs.gov/pubs/abstracts/of.03-263.htm.
Average August stream temperature (AugustTemp)	NorWeST average August stream temperature for a historical climate period of 1993-2011 (Scenario 1). Provides a consistent measure of temperature among reaches in the study area.	Temperature dataset developed by Isaak et al. (2017b) for NHDPlus reaches. Downloaded from the NorWeST website at https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html.
Average stream conductivity (AvgConduct)	Average August stream conductivity for the period of 2000-2015. Provides a consistent measure of conductivity among reaches in the study area.	Conductivity dataset developed by Olson and Cormier (2019) for NHDPlus reaches. Downloaded from https://edg.epa.gov/metadata/catalog/main/home.page.
Reach slope (Slope)	Slope of stream reaches, provides a measure of physical habitat structure and channel type.	Dataset is value added attribute developed in conjunction with NHDPlus. Dataset was downloaded from http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
Super reach slope (S_Slope)	High-resolution slope of stream reaches, provides a measure of physical habitat structure and channel type.	U.S. Forest Service unpublished dataset
U.S. Forest Service Watershed Condition Framework rating (WCF_USFS_Rate)	Index of watershed integrity for HUC12 basins with more than 5% ownership by the U.S. Forest Service.	Dataset developed by the U.S. Forest Service, downloaded from https://enterprisecontentnew-usfs.hub.arcgis.com/datasets/a73c6dfb582045ab987e8bf3f327dd3b_0

Appendix D (continued). Variables used to develop SSN models for predicting juvenile Chinook salmon and steelhead densities across the project area.

Variable and abbreviation	Definition	Data source
U.S. Forest Service Watershed Condition Framework rating of aquatic habitat conditions (WCF_AQHAB_Rate)	Index of aquatic habitat integrity for HUC12 basins with more than 5% ownership by the U.S. Forest Service.	Dataset developed by the U.S. Forest Service, downloaded from https://enterprisecontentnew-usfs.hub.arcgis.com/datasets/a73c6dfb582045ab987e8bf3f327dd3b_0
U.S. Forest Service Watershed Condition Framework rating of road and trail network densities (WCF_RDTRL_Rate)	Index of watershed integrity based on road and trails densities for HUC12 basins with more than 5% ownership by the U.S. Forest Service.	Dataset developed by the U.S. Forest Service, downloaded from https://enterprisecontentnew-usfs.hub.arcgis.com/datasets/a73c6dfb582045ab987e8bf3f327dd3b_0
Carbonate residual geology (CarbResid)	Watershed area underlain by carbonate residual material based on geologic survey maps.	Dataset developed by U.S. Environmental Protection Agency for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Alkaline intrusive geology (AlkIntru)	Watershed area underlain by alkaline intrusive volcanic rocks based on geologic survey maps.	Dataset developed by U.S. Environmental Protection Agency for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Extrusive volcanic geology (ExtruVol)	Watershed area underlain by volcanic extrusive rocks based on geologic survey maps.	Dataset developed by U.S. Environmental Protection Agency for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Shrub landcover (Shrb2011)	Watershed area classified as shrub landcover from remote sensing imagery.	Dataset developed by U.S. Environmental Protection Agency from the National Landuse Cover Database 2011 for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Grass landcover (Grs2011)	Watershed area classified as grass landcover from remote sensing imagery.	Dataset developed by U.S. Environmental Protection Agency from the National Landuse Cover Database 2011 for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.

Appendix D (continued). Variables used to develop SSN models for predicting juvenile Chinook salmon and steelhead densities across the project area.

Variable and abbreviation	Definition	Data source
Hay landcover (Hay2011)	Watershed area classified as hay landcover from remote sensing imagery.	Dataset developed by U.S. Environmental Protection Agency from the National Landuse Cover Database 2011 for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Crop landcover (Crop2011)	Watershed area classified as crop landcover from remote sensing imagery.	Dataset developed by U.S. Environmental Protection Agency from the National Landuse Cover Database 2011 for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Conifer landcover (Conif2011)	Watershed area classified as conifer landcover from remote sensing imagery.	Dataset developed by U.S. Environmental Protection Agency from the National Landuse Cover Database 2011 for the NHDPlus network, downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Riparian canopy cover (Canopy)	Tree canopy density along stream reaches based on classification of remote sensing imagery.	Percent canopy derived from the National Landuse Cover Database 2011 USFS Tree Canopy Cartographic layer averaged over 1 km stream reaches. Downloaded from https://www.mrlc.gov/nlcd11_data.php
Chinook salmon rating (Chin_Rate)	Chinook salmon Intrinsic Potential ratings for stream reaches.	Dataset provided by the Bonneville Power Administration.
Steelhead rating (STHD_Rate)	Steelhead Intrinsic Potential ratings for stream reaches.	Dataset provided by the Bonneville Power Administration
Road density (RdDens)	Density of roads within a watershed.	Dataset developed by U.S. Environmental Protection Agency from 2010 Census Tiger Lines for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Road crossings in watershed (RdCrsWs)	Density of road and stream intersections within a watershed.	Dataset developed by U.S. Environmental Protection Agency from 2010 Census Tiger Lines for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.

Appendix D (continued). Variables used to develop SSN models for predicting juvenile Chinook salmon and steelhead densities across the project area.

Variable and abbreviation	Definition	Data source
Road density within riparian area (RdDensRp)	Density of roads within a watershed that is also within a 100 meter stream buffer.	Dataset developed by U.S. Environmental Protection Agency from 2010 Census Tiger Lines for the NHDPlus network by Hill et al. (2016). Downloaded from https://www.epa.gov/national-aquatic-resource-surveys/streamcat.
Brook trout density (BRK_Dens)	Number of fish survey sites with brook trout present divided by the area of HUC12 basins where survey sites occurred.	Calculated by U.S. Forest Service using the fish survey datasets published in Isaak et al. (2017c).
Smallmouth bass occurrence prediction (SMTH_Pred)	Probability that smallmouth bass occur within a stream reach.	Dataset developed by Rubenson and Olden (2019) for NHDPlus streams within the Pacific Northwest based on predictions from a species distribution model fit to a large fish survey database. Downloaded from https://databasin.org/datasets/eafa4c3d466a41e790843fb73573437e
Chinook salmon density (CH_Density)	Linear density of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) counted or estimated to occur within a reach and expressed as the number of fish per 100 meters. Fish less than 15 cm were considered to be juveniles for density calculations.	Fish survey datasets contributed by partner agencies within the project area.
Yearly average Chinook salmon density (YearAveCHDens)	Average linear density of juvenile Chinook salmon across all the reaches surveyed during individual years from 2000 through 2018.	Fish survey datasets contributed by partner agencies within the project area.
Steelhead density (OM_Density)	Linear density of juvenile steelhead (*Oncorhynchus mykiss*) counted or estimated to occur within a reach and expressed as the number of fish per 100 meters. Fish less than 15 cm were considered to be juveniles for density calculations.	Fish survey datasets contributed by partner agencies within the project area.
Yearly average steelhead density (YearAveOMDens)	Average linear density of juvenile steelhead across all the reaches surveyed during individual years from 2000 through 2018.	Fish survey datasets contributed by partner agencies within the project area.

[a]Variable abbreviations match the field names in the ArcGIS shapefiles and metadata delivered as part of this report.

Appendix E. Description of historical and future juvenile Chinook salmon and steelhead density scenarios developed for this report.

Scenario	Description
S1_00_18	Historical composite scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed for years 2000-2018.
S2_2000	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2000.
S3_2001	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2001.
S4_2002	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2002.
S5_2003	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2003.
S6_2004	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2004.
S7_2005	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2005.
S8_2006	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2006.
S9_2007	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2007.
S10_2008	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2008.
S11_2009	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2009.
S12_2010	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2010.
S13_2011	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2011.
S14_2012	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2012.

S15_2013	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2013.
S16_2014	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2014.
S17_2015	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2015.
S18_2016	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2016.
S19_2017	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2017.
S20_2018	Historical scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) based on basin-wide average densities observed in 2018.
S21_PredSE	Standard errors of juvenile Chinook salmon (or steelhead) density predictions (fish / 100 m)
S22_1C	Future scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) relative to S1_00_18 associated with an increase of 1˚C mean August stream temperature.
S23_2C	Future scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) relative to S1_00_18 associated with an increase of 2˚C mean August stream temperature.
S24_3C	Future scenario of predicted densities (fish / 100 m) of juvenile Chinook salmon (or steelhead) relative to S1_00_18 associated with an increase of 3˚C mean August stream temperature.

Appendix F. Annotated R script used to fit the SSN models to juvenile Chinook salmon and steelhead density datasets in the Phase 2 project area. Comments in the script are preceded by "##". Note that the .ssn directory files "FDAT_Phase2_ChinookFullLSN-STB.ssn" and "FDAT_Phase2_SteelheadFullLSN-STB.ssn" are used with this script to perform the analysis with the R statistical software and SSN package that are downloaded from the CRAN website (https://cran.r-project.org/).

```
## Load SSN package into R
library("SSN")

##Set working directory to location of directory with .ssn files
setwd("C:\\...")

##Import the data from the .ssn directory files and create a SpatialStreamNetwork
        object with prediction points for reach midpoints
Phase2SSN <- importSSN("FDAT_Phase2_ChinookFullLSN-STB.ssn", predpts = "preds")
##To conduct the analysis for steelhead, modify the above statement to import the file
        "FDAT_Phase2_SteelheadFullLSN-STB.ssn"

##Create distance matrices among stream prediction points
createDistMat(Phase2SSN, predpts = "preds", o.write = TRUE, amongpreds = TRUE)

## Describe the names of the variables in the point.data data.frame for each observed and
        prediction data set
names(Phase2SSN)

## Plot river network and locations of observations
plot(Phase2SSN, lwdLineCol = "afvArea", lwdLineEx = 5, lineCol = "blue", pch = 19, xlab =
"x-coordinate (m)", ylab = "y-coordinate (m)", asp = 1)

## Plot values of observations. If conducting an analysis for steelhead specify "OM_Density" o
        "LOGOM_Density"
brks <- plot(Phase2SSN, "CH_DENSITY", lwdLineCol = "afvArea", lwdLineEx = 5, lineCol =
"black", xlab = "x-coordinate" , ylab = "y-coordinate", asp=1 )

brks <- plot(Phase2SSN, "LOGCH_DENS", lwdLineCol = "afvArea", lwdLineEx = 5, lineCol =
"black", xlab = "x-coordinate", ylab = "y-coordinate", asp=1 )

##plot Torgegram describing autocorrelation in log10 transformed fish density observations
Phase2SSN.Torg <- Torgegram(Phase2SSN, "LOGCH_DENS", nlag = 15, nlagcutoff = 1,
maxlag = 50000)
plot(Phase2SSN.Torg)

##Fit SSN model to fish density dataset (this step takes ~5 days on fast desktop)
##Covariates preceded by 'x' indicate quadratic effects
```

```
Phase2SSN.glmssn1 <- glmssn(LOGCH_DENS ~ YearLogCHD + BRK_DENS + SLOPE +
XSLOPE + S1_93_11 + xS1 + MS_Hist + xMS + CANOPY + xCANOPY + Conif2011 +
Shrb2011 + RdCrsWs + xRdCrsWs + BFI + xBFI + Conduct + xConduct, Phase2SSN,
CorModels = c("locID", "Exponential.tailup", "Exponential.taildown", "Exponential.Euclid"),
addfunccol = "afvArea", EstMeth = "REML")

summary(Phase2SSN.glmssn1)

##Calculate and report AIC values
AIC(Phase2SSN.glmssn1)

##Calculate and report cross-validation statistics with confidence intervals
CrossValidationStatsSSN(Phase2SSN.glmssn1)

##Report variance composition among covariate effects and autocovariance functions
varcomp(Phase2SSN.glmssn1)

##Plot graphs of leave-one-out cross-validation (LOOCV) predictions & SEs
cv.out <- CrossValidationSSN(Phase2SSN.glmssn1)
par(mfrow = c(1, 1))
plot(Phase2SSN.glmssn1$sampinfo$z,cv.out[, "cv.pred"], pch = 19, xlab = "Observed Data",
ylab = "LOOCV Prediction")

##Save LOOCV predictions & SEs to working directory file
write.csv(cv.out, "cv_out_ChinookFull-STB.csv", row.names = FALSE)

##Plot model predicted fish density values at 250m prediction points
Phase2SSN.preds <- predict(Phase2SSN.glmssn1, "preds")
plot(Phase2SSN.preds, SEcex.max = 1.4, SEcex.min = .7/3*2, breaktype = "user", brks = brks)

##Save predicted fish density values and SEs at 250m prediction points to working directory file
Phase2SSN.preds <- predict(Phase2SSN.glmssn1, "preds")
pred1df <- getSSNdata.frame(Phase2SSN.preds, "preds")
write.csv(pred1df, "Preds_ChinookFull-STB.csv", row.names = FALSE)
```

Appendix G. Metadata for ArcGIS shapefiles of observed and predicted Chinook salmon and steelhead density datasets.

Citation

Originator

USDA Forest Service, Rocky Mountain Research Station, Air, Water, and Aquatic Sciences Program, Boise Aquatic Science Lab.

Publication Date

April 30, 2020

Title

Modeled juvenile Chinook salmon and steelhead density estimates for northeast Oregon and Idaho at a 250-m mapping resolution on 1:100,000 scale NHDPlus stream line data.

Abstract

These geospatial data were generated by the USDA Forest Service, Rocky Mountain Research Station, Boise Aquatic Sciences Lab in association with the Analysis of Spatial Stream Networks for Salmonids project that was funded by the Bonneville Power Administration. These data represent modeled Chinook salmon and steelhead juvenile density estimates for the period 2000-2018. The data extent comprises portions of the Lower Snake, Salmon, Clearwater, and John Day six-digit Hydrologic Unit Codes, in Oregon and Idaho. Reach density estimates were predicted from geospatial covariates of stream habitat using spatial statistical network (SSN) models fit to sampling datasets of juvenile fish surveys for Chinook salmon (n = 6,757) and steelhead (n = 7,436). The final model for Chinook salmon juvenile densities included statistically significant relationships for seven covariates (reach slope, mean summer flow, mean August stream temperature, baseflow index, riparian canopy density, brook trout density, and inter-annual variation in juvenile densities) and explained 57% of the variation in densities at the survey sites across a potential habitat network of 9,064 km. The final model for steelhead accounted for 48% of the variation in densities at the survey sites across a larger potential habitat network of 18,064 km. The steelhead model included six of the same seven covariates as the Chinook salmon model (watershed conifer coverage replaced baseflow index) but response curves indicated different density-habitat relationships between the two species. The final models were used to create 24 scenarios of juvenile densities throughout the potential habitat networks, which included a baseline composite scenario representing average juvenile densities for 2000-2018 (S1), annual density scenarios from 2000 through 2018 (S2-S20), standard errors of the density predictions (S21), and three future density scenarios associated with increases in mean August stream temperature of 1°C, 2°C, and 3°C (S22-S24).

Supplemental Information

The ArcGIS shapefiles in this dataset are comprised of feature classes for two species (Chinook salmon and steelhead) and three themes (fish density observation data, model predicted fish densities at 250 m prediction points for 24 scenarios, and model predicted fish densities for 250 m stream line segments for 24 scenarios).

Observation point shapefiles are named:

FDAT_Phase2_Chinook_ObservationPoints.shp
FDAT_Phase2_Steelhead_ObservationPoints.shp

Prediction point shapefiles are named:

FDAT_Phase2_Chinook_PredictionPoints_DensityResults.shp
FDAT_Phase2_Steelhead_PredictionPoints_DensityResults.shp

Prediction segment shapefiles are named:

FDAT _Phase2_Chinook_StreamSegmentScenarios_DensityResults.shp
FDAT _Phase2_Steelhead_StreamSegmentScenarios_DensityResults.shp

The GIS framework for these products is the 1:100,000 scale medium resolution NHDPlus Version 2 dataset (https://nhdplus.com/NHDPlus/NHDPlusV2_home.php). The NHDPlus was edited to remove braids, diversions, and other non-dendritic features and incorporated into the National Stream Internet (NSI) dataset (https://www.fs.fed.us/rm/boise/AWAE/projects/NationalStreamInternet.html). Chinook and steelhead range extents were determined from the SteamNet fish dataset for the Pacific Northwest (https://www.streamnet.org/) and both fish species ranges were extracted from the NSI to generate the Chinook salmon and steelhead stream line shapefiles. The stream lines were segmented into 250 m reaches for modeling purposes. A midpoint was generated for each 250 m segment and juvenile fish densities were predicted at these midpoints. Densities are attributed to both the prediction points and the stream line shapefiles. A 1:1 relationship exists between features in these point and line shapefiles.

The observation point shapefiles represent the midpoint of instream fish survey reaches. Where surveys were conducted during multiple years at the same location, point features are spatially coincident in the shapefile, with the number of overlapping points representing the number of sample years.

Fish density estimates in the attribute tables are represented by fields named with the prefixes S1-S24. Other fields in the shapefiles represent internal codes, NHDPlus attributes, and modeling covariates.

Citations for works referenced in the attributes metadata:

Hill, R.A., Weber, M.H., Leibowitz, S.G., Olsen, A.R., and Thornbrugh, D.J. 2016. The stream-catchment (StreamCat) dataset: a database of watershed metrics for the conterminous United States. Journal of the American Water Resources Association 52: 120–128.

Isaak, D., Wenger, S., Peterson, E., Ver Hoef, J., Nagel, D., Luce, C., Hostetler, S., Dunham, J., Roper, B., Wollrab, S., Chandler, G., Horan, D., and Parkes-Payne, S. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: A crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research, 53: 9181-9205.

Olson, J.R. and Cormier, S.M., 2019. Modeling Spatial and Temporal Variation in Natural Background Specific Conductivity. *Environmental science & technology*, *53*(8), pp.4316-4325.

Wenger, S.J., C.H. Luce, A.F. Hamlet, D.J. Isaak, and H.M Neville. 2010. Macroscale hydrologic modeling of ecologically relevant flow metrics. Water Resources Research. 46: W09513.

Wolock, D.M. 2003. "Base-flow index grid for the conterminous United States (Open File Rep. 03–263)." Lawrence, KS: U.S. Geological Survey.

Currentness

April 30, 2020

Progress

Complete

Keywords

Chinook salmon, steelhead, Grande Ronde River, John Day River, Snake River, Clearwater River, Salmon River, juvenile fish density, spatial stream network models.

Access Constraints

Distribution and use constraints are determined by Bonneville Power Administration.

Point of Contact

Daniel Isaak, modeling methods
David Nagel, GIS processing

Dataset Credit

Bonneville Power Administration, Fish and Wildlife Planning Division, Portland, OR.

Native Dataset Environment

ESRI shapefile format, version 10.5.1

Attribute Accuracy Report

Juvenile fish density estimates for Chinook explain 57% of the variation in the observation data. Density estimates for steelhead explain 48% of the variation.

Positional Accuracy

Stream line and point locations adhere to 1:100,000 scale USGS standards.

Horizontal Coordinate System

Projection:	Albers
False_Easting:	1500000.00000000
False_Northing:	0.00000000
Central_Meridian:	-114.00000000
Standard_Parallel_1:	43.00000000
Standard_Parallel_2:	47.00000000
Latitude_Of_Origin:	30.00000000
Linear Unit:	Meter

Attributes for shapefiles. Note that some shapefiles will not contain all of these attribute fields.

FDAT_Phase2_Chinook_ObservationPoints.shp,
FDAT_Phase2_Steelhead_ObservationPoints.shp,
FDAT_Phase2_Chinook_PredictionPoints_DensityResults.shp,
FDAT _Phase2_Steelhead_PredictionPoints_DensityResults.shp,
FDAT_Phase2_Chinook_PredictionPoints_DensityResults.shp,
FDAT _Phase2_Steelhead_PredictionPoints_DensityResults.shp

OBSPRED_ID – A unique ID number assigned to each observation instance. An observation instance is a location + year combination. Individual locations may have multiple observation instances when fish density observations were collected from multiple years at the same location.

PERMA_FID – A unique ID number assigned to each observation location. Only one PERMA_FID ID is assigned to each fish density observation location.

YEAR – Year observation data was collected.

POINT_X – X coordinate location of the observation site snapped to the stream line network in the native Albers projection of the observation shapefile.

POINT_Y – Y coordinate location of the observation site snapped to the stream line network in the native Albers projection of the observation shapefile.

SITE_ID – An ID assigned by the agency collecting the fish density observation data.

SOURCE – The collection agency of the fish density observation data.

GNIS_NAME – Stream name where the fish density observation data was collected.

CH_DENSITY – Juvenile Chinook density observed at the point location. Units: fish/100 m.
Or
OM_Density - Juvenile steelhead density observed at the point location. Units: fish/100 m.

WATERBODY – A flag indicating if the observation site was located in a waterbody as defined by the NHDPlusV2 coding system.

COMID – A unique ID assigned to each stream reach in the NHDPlusV2 coding system.

FTYPE – A feature type assigned to each stream reach in the NHDPlusV2 coding system.

FCODE – A feature code assigned to each stream reach in the NHDPlusV2 coding system.

TotDASqKM – Total drainage area at the observation location as determined by the NHDPlusV2 coding system. Units: square km.

SLOPE – Slope of stream reaches, provides a measure of physical habitat structure and channel type. Dataset is value added attribute developed in conjunction with NHDPlusV2.

NrWst_S1_C – Average August stream conductivity for the period of 2000-2015. Provides a consistent measure of conductivity among reaches in the study area. Temperature dataset developed by Isaak et al. (2017) for NHDPlus reaches.

MS_Hist – Mean summer flow in stream reaches for a historical climate period of 1976-1997. Provides a consistent measure of stream size among reaches in the study area. Flow value dataset developed by Wenger et al. (2010) for NHDPlus reaches.

W95_Hist – The number of days with flows exceeding the 95th percentile during the winter. Provides a measure of hydrologic flashiness that differentiates between stream reaches with snowmelt and rainfall runoff regimes. Flow value dataset developed by Wenger et al. (2010) for NHDPlus reaches.

S_SLOPE – High-resolution slope of stream reaches, provides a measure of physical habitat structure and channel type. U.S. Forest Service unpublished dataset.

CANOPY - Tree canopy density along stream reaches based on classification of remote sensing imagery. Percent canopy derived from the National Land Cover Database 2011 USFS Tree Canopy Cartographic layer averaged over 1 km stream reaches.

CarbResid – Watershed area underlain by carbonate residual material based on geologic survey maps. Dataset developed by U.S. Environmental Protection Agency for the NHDPlus network by Hill et al. (2016).

AlkIntru – Watershed area underlain by alkaline intrusive volcanic rocks based on geologic survey maps. Dataset developed by U.S. Environmental Protection Agency for the NHDPlus network by Hill et al. (2016).

ExtruVol – Watershed area underlain by volcanic extrusive rocks based on geologic survey maps. Dataset developed by U.S. Environmental Protection Agency for the NHDPlus network by Hill et al. (2016).

Conif2011 – Watershed area classified as conifer land cover from remote sensing imagery. StreamCat dataset developed by U.S. Environmental Protection Agency from the National Land Cover Database 2011 for the NHDPlus network.

Shrb2011 – Watershed area classified as shrub land cover from remote sensing imagery. StreamCat dataset developed by U.S. Environmental Protection Agency from the National Land Cover Database 2011 for the NHDPlus network by Hill et al. (2016).

Grs2011 – Watershed area classified as grass land cover from remote sensing imagery. StreamCat dataset developed by U.S. Environmental Protection Agency from the National Land Cover Database 2011 for the NHDPlus network by Hill et al. (2016).

Hay2011 – Watershed area classified as hay land cover from remote sensing imagery. StreamCat dataset developed by U.S. Environmental Protection Agency from the National Land Cover Database 2011 for the NHDPlus network by Hill et al. (2016).

Crop2011 – Watershed area classified as crop land cover from remote sensing imagery. StreamCat dataset developed by U.S. Environmental Protection Agency from the National Land Cover Database 2011 for the NHDPlus network by Hill et al. (2016).

RdDens – Density of roads within a watershed. StreamCat dataset developed by U.S. Environmental Protection Agency from 2010 Census Tiger Lines for the NHDPlus network by Hill et al. (2016).

RdDensRp – Density of roads within a watershed that is also within a 100 meter stream buffer. StreamCat dataset developed by U.S. Environmental Protection Agency from 2010 Census Tiger Lines for the NHDPlus network by Hill et al. (2016).

RdCrsWs – Density of road and stream intersections within a watershed. StreamCat dataset developed by U.S. Environmental Protection Agency from 2010 Census Tiger Lines for the NHDPlus network by Hill et al. (2016).

WCF_USFS – U.S. Forest Service Watershed Condition Framework rating. Index of watershed integrity for HUC12 basins with more than 5% ownership by the U.S. Forest Service. Dataset developed by the U.S. Forest Service.

WCF_AQHAB – U.S. Forest Service Watershed Condition Framework rating of road and trail network densities. Index of aquatic habitat integrity for HUC12 basins with more than 5% ownership by the U.S. Forest Service. Dataset developed by the U.S. Forest Service.

WCF_RDTRL – U.S. Forest Service Watershed Condition Framework rating of road and trail network densities. Index of watershed integrity based on road and trails densities for HUC12 basins with more than 5% ownership by the U.S. Forest Service. Dataset developed by the U.S. Forest Service.

CHINRATE - Chinook salmon Intrinsic Potential ratings for stream reaches. Dataset provided by the Bonneville Power Administration.
Or
STHDRATE - Steelhead Intrinsic Potential ratings for stream reaches. Dataset provided by the Bonneville Power Administration.

HUC_8 – 8-digit hydrologic unit code from the USGS Watershed Boundary Dataset.

HUC_12- 12-digit hydrologic unit code from the USGS Watershed Boundary Dataset.

AREA_SQKM – Area of the 12-digit HUC used for computing brook trout density (BRK_DENS). Units: square kilometers.

BRK_DENS – Number of fish survey sites with brook trout present divided by the area of HUC_12 basins where survey sites occurred. Calculated by U.S. Forest Service using the fish survey datasets published in Isaak et al. (2017).

SMTH_PRED – Probability that smallmouth bass occur within a stream reach. Dataset developed by Rubenson and Olden (2019) for NHDPlus streams within the Pacific

Northwest based on predictions from a species distribution model fit to a large fish survey database.

CH_POP_ID – Designated distinct Chinook population ID number.
Or
SH_POP_ID - Designated distinct Steelhead population ID number.

CH_POP – Designated distinct Chinook population name.
Or
SH_POP - Designated distinct steelhead population name.

BFI – Base-flow ratio for stream reaches calculated as the ratio of summer low flows to total annual flow and expressed as a percentage. Sites with larger baseflow values have more stable hydrographs and groundwater contributions. Dataset developed by Wolock (2003).

AvgConduct – Average August stream conductivity for the period of 2000-2015. Provides a consistent measure of conductivity among reaches in the study area. Conductivity dataset developed by Olson and Cormier (2019) for NHDPlus reaches.

S1_00_18 – Predicted average juvenile fish density for years 2000-2018. Units: fish/100 m.

S2_2000 – Predicted juvenile fish density for year 2000. Units: fish/100 m.

S3_2001 – Predicted juvenile fish density for year 2001. Units: fish/100 m.

S4_2002 – Predicted juvenile fish density for year 2002. Units: fish/100 m.

S5_2003 – Predicted juvenile fish density for year 2003. Units: fish/100 m.

S6_2004 – Predicted juvenile fish density for year 2004. Units: fish/100 m.

S7_2005 – Predicted juvenile fish density for year 2005. Units: fish/100 m.

S8_2006 – Predicted juvenile fish density for year 2006. Units: fish/100 m.

S9_2007 – Predicted juvenile fish density for year 2007. Units: fish/100 m.

S10_2008 – Predicted juvenile fish density for year 2008. Units: fish/100 m.

S11_2009 – Predicted juvenile fish density for year 2009. Units: fish/100 m.

S12_2010 – Predicted juvenile fish density for year 2010. Units: fish/100 m.

S13_2011 – Predicted juvenile fish density for year 2011. Units: fish/100 m.

S14_2012 – Predicted juvenile fish density for year 2012. Units: fish/100 m.

S15_2013 – Predicted juvenile fish density for year 2013. Units: fish/100 m.

S16_2014 – Predicted juvenile fish density for year 2014. Units: fish/100 m.

S17_2015 – Predicted juvenile fish density for year 2015. Units: fish/100 m.

S18_2016 – Predicted juvenile fish density for year 2016. Units: fish/100 m.

S19_2017 – Predicted juvenile fish density for year 2017. Units: fish/100 m.

S20_2018 – Predicted juvenile fish density for year 2018. Units: fish/100 m.

S21_SE – Standard error of the predicted density estimates.

S22_1C – Predicted future juvenile fish density assuming a 1 degree Celsius increase in mean August stream temperature. Units: fish/100 m.

S23_2C – Predicted future juvenile fish density assuming a 2 degree Celsius increase in mean August stream temperature. Units: fish/100 m.

S24_3C – Predicted future juvenile fish density assuming a 3 degree Celsius increase in mean August stream temperature. Units: fish/100 m.