Supplementary Data

Habitat Suitability Index

Node definitions

Bull trout occurrence probability (ψ) was predicted as a function of four predictors, which were primary nodes in our BN. The four probabilities, initially predicted as four continuous variables, were each reclassified into categorical variables (Table 1) exhibiting low (0 to 0.33), moderate (0.34 to 0.66), or high (0.67 to 1) values (Table 2). Conditional probabilities defining relations among nodes were estimated from empirically-derived logistic functions that incorporated errors associated with intercept (β_0) and slope (β_1) estimates of covariate (x), and whose general formula was:

$$P(\psi \mid x, \beta_0, \beta_1) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x)}}$$

We verified that parameter estimates and errors were normally distributed, $X \sim \mathcal{N}(\mu, \sigma^2)$, for all occurrence-habitat relations in the HSI. Equations for each of the four HSI variables, which immediately follow, were taken from previously published logistic regressions (stream size, winter stream flow, stream gradient; Wenger et al. 2011, and stream temperature; Dunham et al. 2003)

Gradient—Stream reaches with steep gradients are often unsuitable habitat for trout (e.g., large substrate, high current velocity) and may serve as velocity barriers to upstream dispersal. As such, gradient (GRAD) is often included in models predicting the distribution of bull trout (Dunham and Rieman 1999; Rich et al. 2003; Wenger et al. 2011). We predicted bull trout occurrence (ψ_{grad}) as a linear function of gradient (%; x_{grad}), using parameter estimates from

Wenger et al. (2011).Values for the beta and intercept were as follows: $\beta_{grad}(\mu = -0.80, \sigma^2 = 0.25)$, $int\ (\mu = 0.85, \sigma^2 = 0.50)$, and the formula was:

$$P(\psi_{grad} \mid x_{grad}, int, \beta_{grad}) = \frac{1}{1 + e^{-(int + \beta_{grad} x_{grad})}}$$

Mean summer stream flow—We used mean summer flow (m^3/s; sflow) as a proxy for stream size. Mean summer flow estimates were derived using output from a variable infiltration capacity (VIC) macro-scale hydrologic model (Liang et al. 1994; Elsner et al. 1999; Wenger et al. 2010). Briefly, the VIC model is a physically based model that balances surface energy and water fluxes based on empirically-derived relationships among infiltration, runoff, and base flow processes. Estimates were made for each valley segment at daily time steps and metrics were averaged across a 20 year period (1977-1997). The mean summer flow (SFLOW) was the average daily flow starting the first day after June 1 when flows were below the mean annual flow value, and ending on 30 September. This method ensured that the summer period began following the subsidence of snowmelt flooding. We predicted bull trout occurrence (ψ_{sflow}) as a quadratic function of stream size (x_{sflow}) using parameter estimates from Wenger et al. (2011), using the method described above. Values for the betas and intercept were: $\beta_{sflow}(\mu = 0.91, \sigma^2 = 0.21)$, ${\beta_{sflow}}^2(\mu = 0.11, \sigma^2 = 0.05)$, $int\ (\mu = 0.85, \sigma^2 = 0.10)$, and the formula was:

$$P(\psi_{sflow} \mid x_{sflow}, int, \beta_{sflow}, {\beta_{sflow}}^2) = \frac{1}{1 + e^{-(int + \beta_{sflow} x_{sflow} + {\beta_{sflow}}^2 x_{sflow})}}$$

Winter high flow events—Scouring flows are a significant source of early life stage mortality, causing lower egg survival resulting from redd scour (Montgomery et al. 1996), and increased fry mortality through downstream displacement (Fausch et al. 2001). As a result, bull trout likely avoid or experience reduced spawning and rearing success in reaches with a higher frequency of winter flows and occurrence has been shown to be less likely in stream reaches with flow regimes that have many high flow events per year (W95; Wenger et al. 2011). We used the W95 metric developed by Wenger et al. (2010) as a measure of winter high flow events. The W95 was calculated based on output from the VIC macro-scale hydrologic model (Wenger et al. 2010), and represented the frequency of high flows in winter (1 December to 28 February). We reasoned that this is the period within which bull trout redds are most susceptible to scour, and fry are most likely to be displaced by high flows. The W95 was a count of the number of days that flows were in the top 5% within the 1 December to 28 February period, averaged over the 20 year period 1977-1997. We predicted bull trout occurrence (ψ_{W95}) as a linear function of winter high flow events (x_{W95}), using parameter estimates from Wenger et al. (2011). Values for the beta and intercept were as follows: $\beta_{W95}(\mu = -1.52, \sigma^2 = 0.29)$, $int\ (\mu = 0.85, \sigma^2 = 0.10)$, and the formula was:

$$P(\psi_{W95} \mid x_{W95}, int, \beta_{W95}) = \frac{1}{1 + e^{-(int + \beta_{W95} x_{W95})}}$$

Maximum annual temperature—The LST model was used to predict maximum annual stream temperature (MAT) every 1000 m throughout the Wenatchee River basin (see text for details). Estimates of MAT were available for the period 2001-2010. The average across the 10 years (TMAX) and the resulting standard deviation for each 1000 m estimate were incorporated into the HSI to allow for uncertainty in inter-annual variation in temperatures, assuming a normal distribution $X \sim \mathcal{N}(\mu, \sigma^2)$. We predicted bull trout occurrence (ψ_{temp}) as a linear function of the previously described values (x_{temp}) using parameter estimates from Dunham et al. (2003). Values for the beta and intercept were as follows: $\beta_{temp}(\mu = -0.38, \sigma^2 = 0.09)$, $int\ (\mu = 5.47, \sigma^2 = 1.40)$, and the formula was:

$$P(\psi_{temp} \mid x_{temp}, int, \beta_{temp}) = \frac{1}{1 + e^{-(int + \beta_{temp} x_{temp})}}$$

Habitat suitability

Bull trout habitat suitability (HSI) was based on the relative contribution of the four predictor variables (GRAD, W95,TMAX, and SFLOW). Probabilities were derived every 200 m along the stream network for each predictor, continuous values of each were reclassified, and the four component conditions were used to assign a composite HSI categorical value of low, moderate, or high. These states reflected weighted combinations of the bull trout occurrence probability according to each predictor. For example, if the four component predictor values of an individual sub-reach were all classified as “High”, the composite HSI state=High. Conversely, if all four were “Low”, HSI=Low. For intermediate cases, we weighted the influence of the predictors according to their average effect size from the published literature (GRAD = 0.8, W95 = 1.5, TMAX = 2.4, SFLOW = 1.15), and populated the CPT table as follows. First, we gave each potential state a numeric value (Low = 1, Moderate = 2, High = 3). Second, for each possible combination of state by habitat factor ($N = 3^4 = 81$) we multiplied the state value by the corresponding weight and summed the four resulting values. For example, this index value for the combination GRAD = Low, W95 = Moderate, TMAX = High, SFLOW = Moderate [1(0.8) + 2(1.5) + 3(2.4) + 2(1.15)] is 10.8. The distribution of these index values across all 81 combinations was normal (Fig. S1). Finally, we uniformly distributed conditional probabilities across all possible combinations of states for the four factors based on Table S1. The resulting CPT is presented in Table S2.

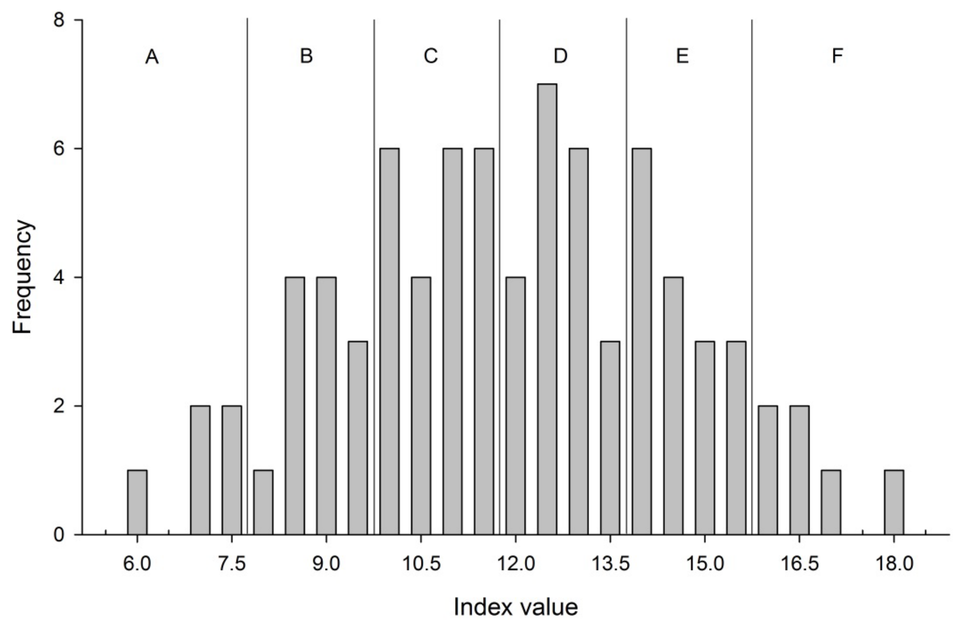


Fig. S1. Histogram of HSI values for all stream reaches in the Wenatchee River basin. Regions (A-F) indicate ranges of values for which various conditional probabilities were applied (Table S1).

Table S1. Schema used to calculate conditional probabilities for a bull trout habitat suitability index.

Index value	Low	Moderate	High
<6.00	100	0	0
A (6.01-7.75)	90	10	0
B (7.76-9.75)	75	25	0
C (9.76-11.75)	25	75	0
D (11.76-13.75)	0	75	25
E (13.76-15.75)	0	25	75
F (15.76-17.00)	0	10	90
>17	0	0	100

Table S2. Conditional probability table for a bull trout habitat suitability index for the Wenatchee River basin, Washington.

Physical habitat factor				HSI state		
MAXT	GRAD	W95	SFLOW	Low	Moderate	High
LOW	LOW	LOW	LOW	100	0	0
LOW	LOW	LOW	MODERATE	90	10	0
LOW	LOW	LOW	HIGH	75	25	0
LOW	LOW	MODERATE	LOW	90	10	0
LOW	LOW	MODERATE	MODERATE	75	25	0
LOW	LOW	MODERATE	HIGH	75	25	0
LOW	LOW	HIGH	LOW	75	25	0
LOW	LOW	HIGH	MODERATE	25	75	0
LOW	LOW	HIGH	HIGH	25	75	0
LOW	MODERATE	LOW	LOW	90	10	0
LOW	MODERATE	LOW	MODERATE	90	10	0
LOW	MODERATE	LOW	HIGH	75	25	0
LOW	MODERATE	MODERATE	LOW	75	25	0
LOW	MODERATE	MODERATE	MODERATE	75	25	0
LOW	MODERATE	MODERATE	HIGH	25	75	0
LOW	MODERATE	HIGH	LOW	75	25	0
LOW	MODERATE	HIGH	MODERATE	25	75	0
LOW	MODERATE	HIGH	HIGH	0	75	25
LOW	HIGH	LOW	LOW	90	10	0
LOW	HIGH	LOW	MODERATE	75	25	0
LOW	HIGH	LOW	HIGH	25	75	0
LOW	HIGH	MODERATE	LOW	75	25	0
LOW	HIGH	MODERATE	MODERATE	25	75	0
LOW	HIGH	MODERATE	HIGH	25	75	0
LOW	HIGH	HIGH	LOW	25	75	0
LOW	HIGH	HIGH	MODERATE	25	75	0
LOW	HIGH	HIGH	HIGH	0	75	25
MODERATE	LOW	LOW	LOW	75	25	0
MODERATE	LOW	LOW	MODERATE	75	25	0
MODERATE	LOW	LOW	HIGH	25	75	0
MODERATE	LOW	MODERATE	LOW	75	25	0
MODERATE	LOW	MODERATE	MODERATE	25	75	0
MODERATE	LOW	MODERATE	HIGH	0	75	25
MODERATE	LOW	HIGH	LOW	25	75	0
MODERATE	LOW	HIGH	MODERATE	0	75	25
MODERATE	LOW	HIGH	HIGH	0	75	25
MODERATE	MODERATE	LOW	LOW	75	25	0

MODERATE	MODERATE	LOW	MODERATE	25	75	0
MODERATE	MODERATE	LOW	HIGH	25	75	0
MODERATE	MODERATE	MODERATE	LOW	25	75	0
MODERATE	MODERATE	MODERATE	MODERATE	0	75	25
MODERATE	MODERATE	MODERATE	HIGH	0	75	25
MODERATE	MODERATE	HIGH	LOW	0	75	25
MODERATE	MODERATE	HIGH	MODERATE	0	75	25
MODERATE	MODERATE	HIGH	HIGH	0	25	75
MODERATE	HIGH	LOW	LOW	25	75	0
MODERATE	HIGH	LOW	MODERATE	25	75	0
MODERATE	HIGH	LOW	HIGH	0	75	25
MODERATE	HIGH	MODERATE	LOW	25	75	0
MODERATE	HIGH	MODERATE	MODERATE	0	75	25
MODERATE	HIGH	MODERATE	HIGH	0	75	25
MODERATE	HIGH	HIGH	LOW	0	75	25
MODERATE	HIGH	HIGH	MODERATE	0	25	75
MODERATE	HIGH	HIGH	HIGH	0	25	75
HIGH	LOW	LOW	LOW	25	75	0
HIGH	LOW	LOW	MODERATE	0	75	25
HIGH	LOW	LOW	HIGH	0	75	25
HIGH	LOW	MODERATE	LOW	0	75	25
HIGH	LOW	MODERATE	MODERATE	0	75	25
HIGH	LOW	MODERATE	HIGH	0	25	75
HIGH	LOW	HIGH	LOW	0	25	75
HIGH	LOW	HIGH	MODERATE	0	25	75
HIGH	LOW	HIGH	HIGH	0	10	90
HIGH	MODERATE	LOW	LOW	25	75	0
HIGH	MODERATE	LOW	MODERATE	0	75	25
HIGH	MODERATE	LOW	HIGH	0	25	75
HIGH	MODERATE	MODERATE	LOW	0	75	25
HIGH	MODERATE	MODERATE	MODERATE	0	25	75
HIGH	MODERATE	MODERATE	HIGH	0	25	75
HIGH	MODERATE	HIGH	LOW	0	25	75
HIGH	MODERATE	HIGH	MODERATE	0	10	90
HIGH	MODERATE	HIGH	HIGH	0	10	90
HIGH	HIGH	LOW	LOW	0	75	25
HIGH	HIGH	LOW	MODERATE	0	75	25
HIGH	HIGH	LOW	HIGH	0	25	75
HIGH	HIGH	MODERATE	LOW	0	25	75
HIGH	HIGH	MODERATE	MODERATE	0	25	75
HIGH	HIGH	MODERATE	HIGH	0	10	90
HIGH	HIGH	HIGH	LOW	0	25	75
HIGH	HIGH	HIGH	MODERATE	0	10	90

HIGH	HIGH	HIGH	HIGH	0	0	100

Bull Trout Vulnerability Belief Network

Table S3. Conditional probability table for local effects of fire on bull trout in the Wenatchee River basin, Washington, USA.

Input node			State (Local effects of fire)		
ΔHSI	FLEST	PREFIRE	Low	Moderate	High
0 to 5	Low	None	90	10	0
0 to 5	Low	Low	80	20	0
0 to 5	Low	Moderate	40	60	0
0 to 5	Low	High	30	60	10
0 to 5	Moderate	None	90	10	0
0 to 5	Moderate	Low	70	30	0
0 to 5	Moderate	Moderate	50	40	10
0 to 5	Moderate	High	40	40	20
0 to 5	High	None	90	10	0
0 to 5	High	Low	90	10	0
0 to 5	High	Moderate	80	20	0
0 to 5	High	High	70	20	10
5 to 15	Low	None	90	10	0
5 to 15	Low	Low	70	30	0
5 to 15	Low	Moderate	10	80	10
5 to 15	Low	High	10	50	40
5 to 15	Moderate	None	90	10	0
5 to 15	Moderate	Low	60	40	0
5 to 15	Moderate	Moderate	0	80	20
5 to 15	Moderate	High	0	30	70

5 to 15	High	None	90	10	0
5 to 15	High	Low	0	40	60
5 to 15	High	Moderate	0	30	70
5 to 15	High	High	0	20	80
>15	Low	None	90	10	0
>15	Low	Low	70	30	0
>15	Low	Moderate	0	70	30
>15	Low	High	0	60	40
>15	Moderate	None	90	10	0
>15	Moderate	Low	0	60	40
>15	Moderate	Moderate	0	40	60
>15	Moderate	High	0	20	80
>15	High	None	90	10	0
>15	High	Low	0	30	70
>15	High	Moderate	0	20	80
>15	High	High	0	10	90

Table S4. Conditional probability table for intervening passage of bull trout among habitat patches in the Wenatchee River basin, Washington.

Input node		Intervening passage (state)		
PATCHDIST	ROADX	Low	Moderate	High
Adjacent	None	0	10	90
Adjacent	1-5	0	20	80
Adjacent	5-14	0	30	70
Adjacent	>14	25	50	25
Near	None	0	20	80
Near	1-5	0	30	70
Near	5-14	25	50	25
Near	>14	30	60	10
Moderate	None	0	30	70
Moderate	1-5	25	50	25
Moderate	5-14	30	60	10
Moderate	>14	50	50	0
Far	None	0	75	25
Far	1-5	25	50	25
Far	5-14	40	60	0
Far	>14	90	10	0

Table S5. Conditional probability table for recolonization potential of bull trout among habitat patches in the Wenatchee River basin, Washington.

Input Node		Recolonization potential (state)		
ABVBAR	INTERV	Low	Moderate	High
YES	Low	90	10	0
YES	Moderate	80	20	0
YES	High	70	30	0
NO	Low	0	50	50
NO	Moderate	0	25	75
NO	High	0	10	90

Table S6. Conditional probability table for bull trout vulnerability to wildfire in the Wenatchee River basin, Washington, USA.

Input nodes			Vulnerability (state)		
PATCHSIZE	RECOL	LOCAL	Low	Moderate	High
SMALL	Low	Low	0	30	70
SMALL	Low	Moderate	0	20	80
SMALL	Low	High	0	10	90
SMALL	Moderate	Low	0	40	60
SMALL	Moderate	Moderate	0	30	70
SMALL	Moderate	High	0	20	80
SMALL	High	Low	0	50	50
SMALL	High	Moderate	0	40	60
SMALL	High	High	0	30	70
MEDIUM	Low	Low	10	80	10
MEDIUM	Low	Moderate	0	70	30
MEDIUM	Low	High	0	60	40
MEDIUM	Moderate	Low	30	60	10
MEDIUM	Moderate	Moderate	10	80	10
MEDIUM	Moderate	High	0	70	30
MEDIUM	High	Low	40	60	0
MEDIUM	High	Moderate	30	60	10
MEDIUM	High	High	10	80	10
LARGE	Low	Low	70	30	0
LARGE	Low	Moderate	60	40	0
LARGE	Low	High	50	50	0
LARGE	Moderate	Low	80	20	0

LARGE	Moderate	Moderate	70	30	0
LARGE	Moderate	High	60	40	0
LARGE	High	Low	90	10	0
LARGE	High	Moderate	80	20	0
LARGE	High	High	70	30	0

Vulnerabilty Maps

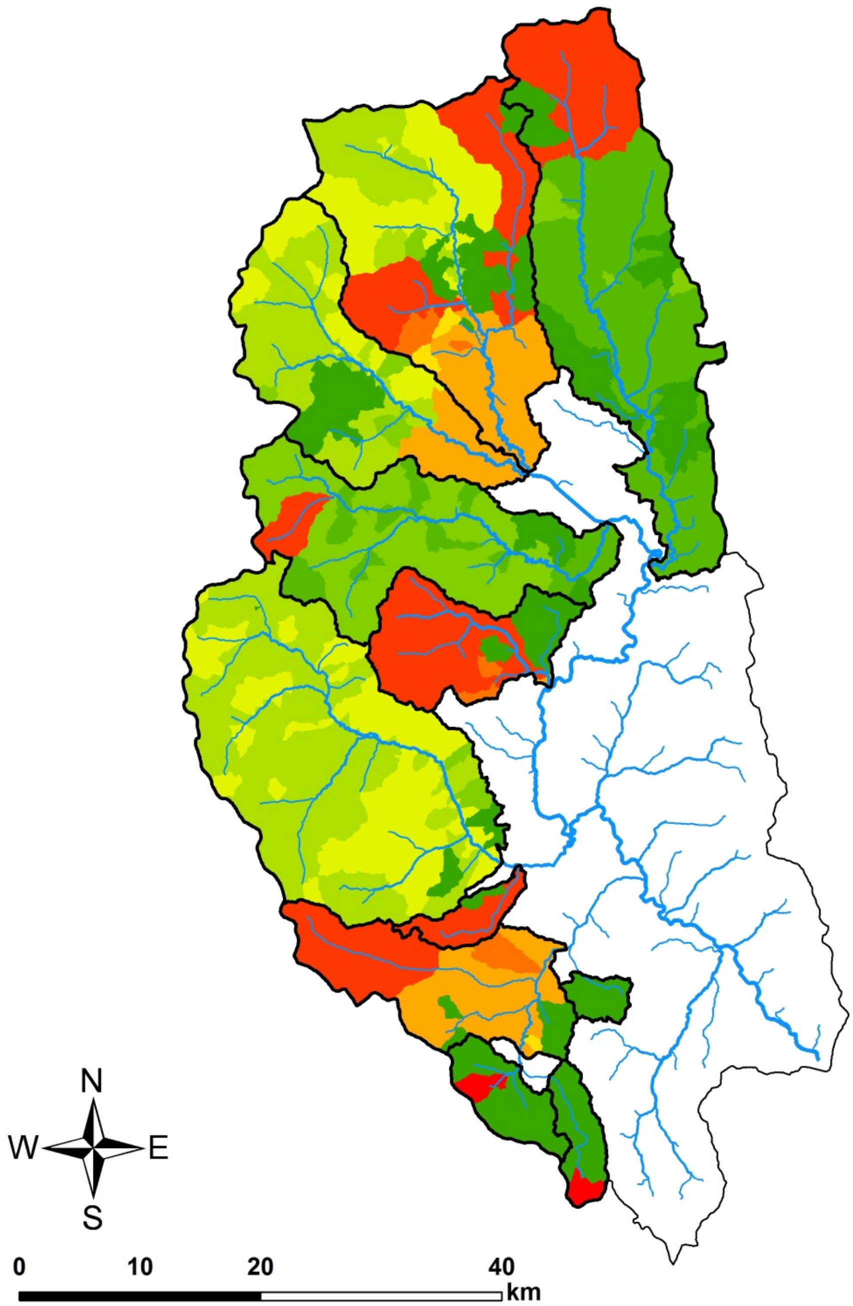


Fig. S2. Vulnerability of bull trout populations in 11 patches to wildfire in the Wenatchee River basin, Washington, USA (see Fig. 1 for detailed location information) under current (2012) conditions. Shading represents estimated vulnerability to fire (green = low, yellow/orange = moderate, and red = high), and the stream network (second order and higher streams) is shown for reference (blue lines). See text for details on how vulnerability was estimated.

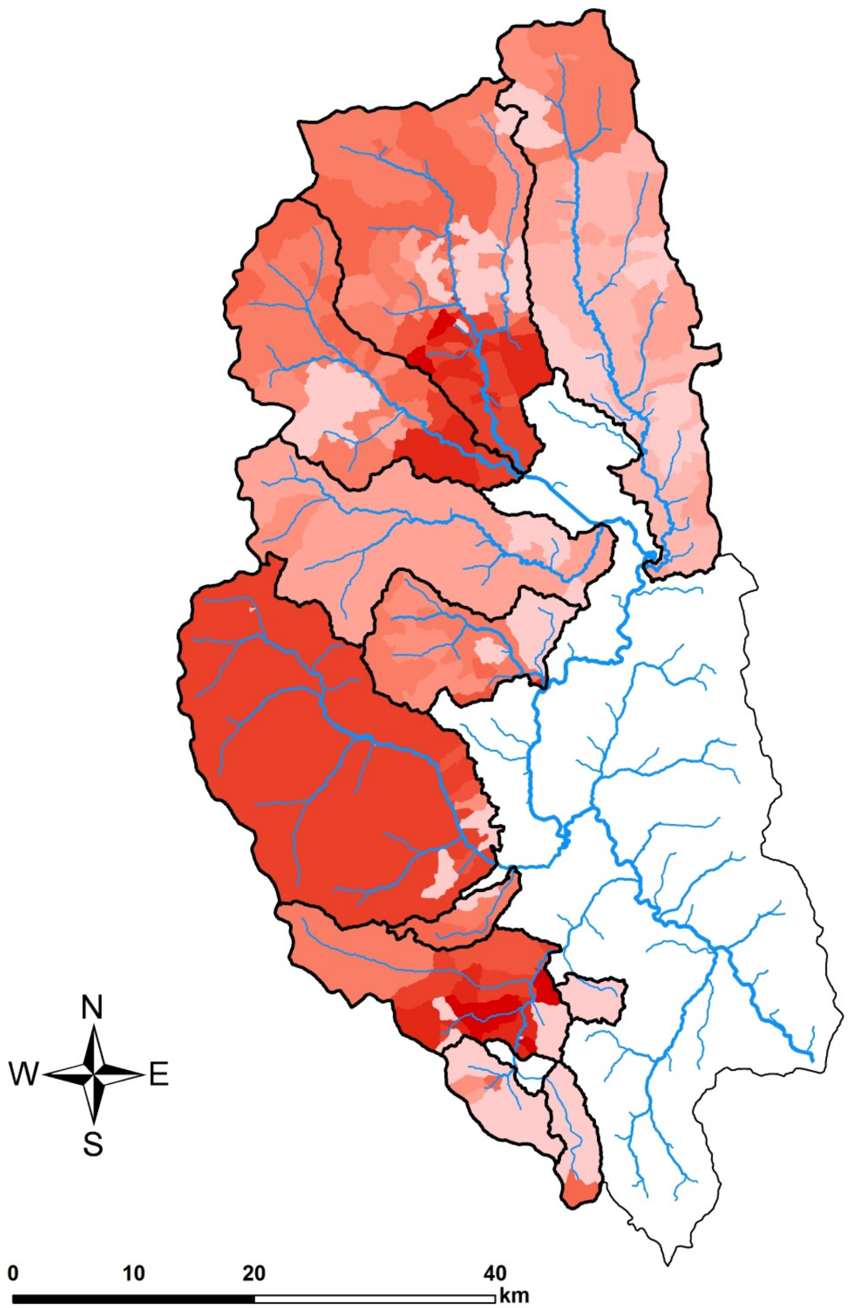


Fig. S3. Uncertainty associated with vulnerability classification of bull trout populations in 11 patches to wildfire in the Wenatchee River basin, Washington, USA (see Fig. 1 for detailed location information) under current (2012) conditions. Shading represents level of uncertainty in vulnerability classification (light pink to red = low to high uncertainty), and the stream network (second order and higher streams) is shown for reference (blue lines). See text for details on how uncertainty was estimated.

Scour Likelihood and Stream Size Figures

Fig. S4. Histogram of predicted winter high flow frequencies (number of days with flows > 90^{th} percentile during that year) for all reaches in the Wenatchee River basin, Washington, USA, for the recent past (1978-1997; a) and three future (2040s) climate change climate scenarios: P = low warming (b), C = moderate warming (c), and M = high warming (d). Estimates were derived using the VIC macroscale hydrologic model for streams (Wenger et al. 2010, 2011).

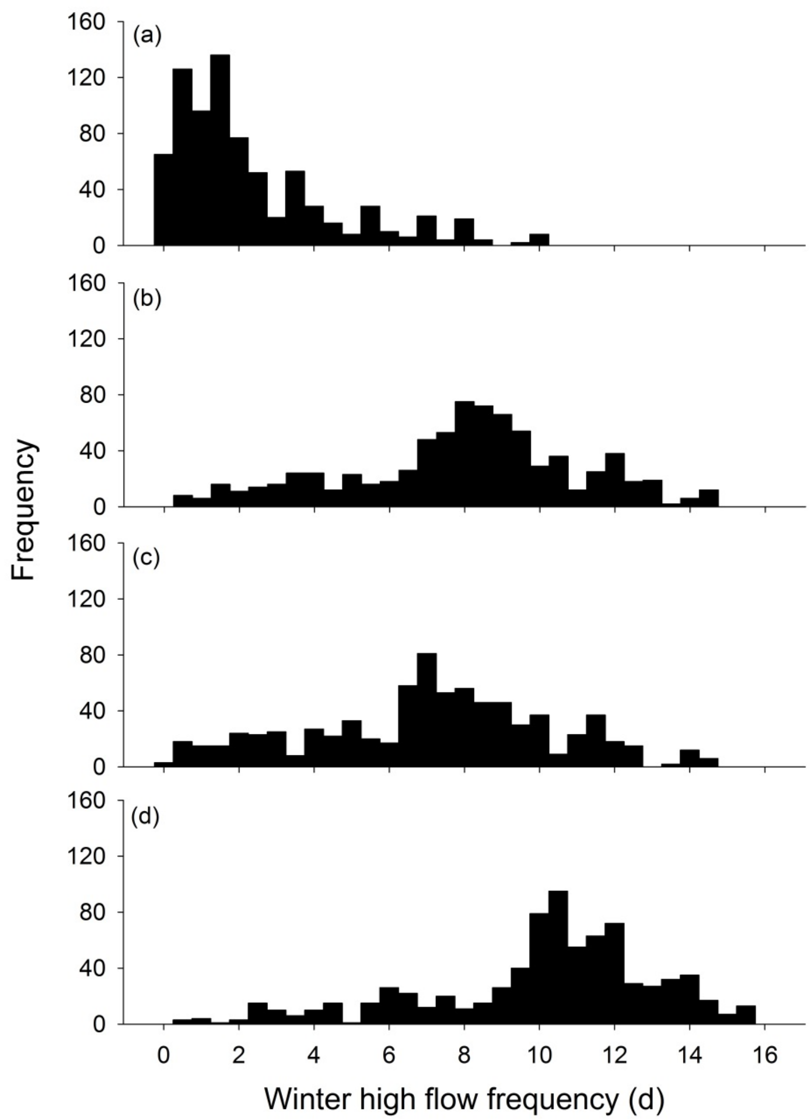
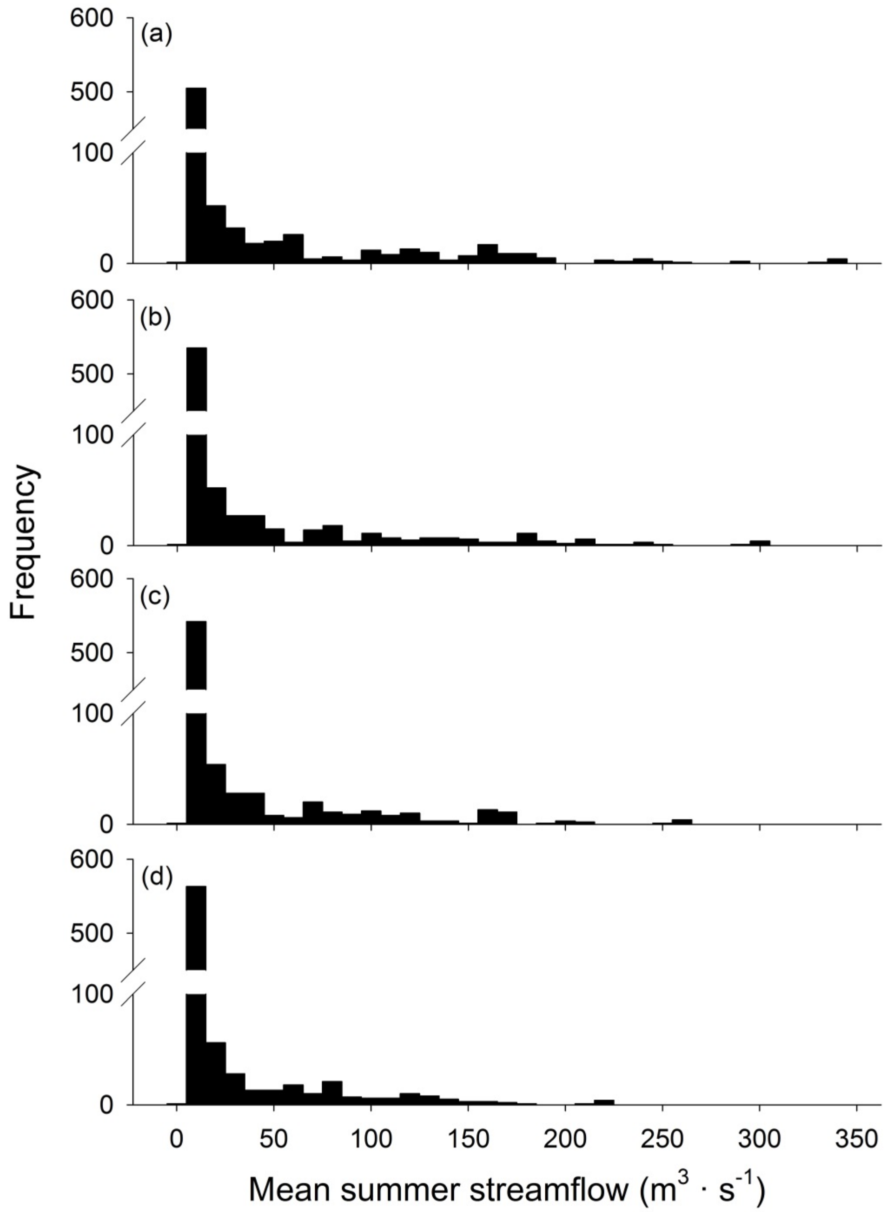


Fig. S5. Histogram of predicted mean summer stream flow (m^3/s) for all reaches in the Wenatchee River basin, Washington, USA, for the recent past (1978-1997; a) and three future (2040s) climate change climate scenarios: P = low warming (b), C = moderate warming (c), and M = high warming (d). Estimates were derived using the VIC macro-scale hydrologic model for streams (Wenger et al. 2010, 2011).



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