Isaak, D.J., M.K. Young, D.L. Horan, D. Nagel, M.K. Schwartz, and K.S. McKelvey. Do metapopulations and management matter for relict headwater bull trout populations in a warming climate? Ecological Applications

Appendix S3, Table S1. Covariates used to describe natal habitat patches for bull trout occupancy models.

Covariate	Predicted effect on occupancy, definition, and rationale	Data source
Elevation (Ele)	Positive effect. Elevation of patch pour-point, which was often used as a surrogate for stream temperature in early climate assessments. References: Rieman et al. 2007, Buisson and Grenouillet 2009	30-m National Elevation Dataset digital elevation model http://ned.usgs.gov/
Patch length (PL)[1]	Positive effect. Length of contiguous 1-km stream reaches (> 3 km) that have mean August temperatures ≤ 11°C, summer flows ≥ 0.0057 m^3/s and reach slopes ≤ 15%, which serve as potential natal habitats where bull trout adults spawn and juveniles grow for two or more years. Habitat size is positively correlated with population occurrence, population size, and life history and habitat diversity that buffer populations against stochastic disturbances that are common in mountain environments. It is also associated with resistance to brook trout replacement. References: Hanski 1991; Lande 1993; Rieman and McIntyre 1995; Dunham and Rieman 1999; Hilderbrand and Kershner 2000; Rieman et al. 2006; Wilcox et al. 2018.	Historical baseline scenario bull trout patches from the Climate Shield Cold-Water Refuge Streams for Native Trout website: https://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html
Patch volume (PV)	Positive effect. Volume is a representation of patch size developed by multiplying patch length by the average summer flow through the 1-km reaches composing a patch. Water yields vary per unit area across the hydroclimatically diverse study area where streams draining wetter basins may provide greater habitat volumes to support bull trout populations within a given length of stream. Patch volume may also portray patch size more accurately where impassible barriers such as waterfalls limit bull trout to downstream reaches of patches that otherwise have larger upstream areas of suitable habitat. Finally, trout abundance in small streams scales more directly with stream volume than with length. References: Same as above for patch length but also Young et al. 2005; Hortness 2006; Koizumi 2011; Bieger et al. 2015; Hudson et al. 2019.	Calculated for historical baseline scenario as described in text using data from the Climate Shield Cold-Water Refuge Streams for Native Trout website: https://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html and the Western U.S. Stream Flow Metrics website: https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml
Minimum temperature (MinT)[1]	Negative effect. Coldest mean August temperature of a 1-km reach within a natal patch. Particularly cold reaches may provide a thermal	Historical baseline stream temperature scenario from the NorWeST Regional Database and Modeled Stream

	refuge for bull trout during warm periods or preclude a complete brook trout invasion throughout a patch due to the latter species' warmer thermal niche. References: Isaak et al. 2015, 2017b; Howell 2018.	Temperatures website: https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html
Valley bottom confinement (VBC)	Positive effect. The proportion of a natal patch that is bordered by unconfined valleys rather than V-shaped valleys directly adjacent to hillslopes. Unconfined streams are less susceptible to high-severity flooding or disturbances such as wildfires and debris flows that originate on hillslopes. Unconfined streams also have greater amounts of subsurface hyporheic flows that provide warmer winter incubation habitat for bull trout eggs and colder summer rearing habitat for juveniles. References: Baxter and Hauer 2000; Wenger et al. 2011; Nagel et al. 2014; Bean et al. 2015.	Valley bottom confinement grid layer from the Valley Bottom Algorithm website: https://www.fs.fed.us/rm/boise/AWAE/projects/valley_confinement.shtml
Slope (S)[1]	Negative effect. Reach slope values averaged across all the 1-km reaches composing a natal habitat patch. Patches with low slopes are generally preferred by bull trout due to the greater availability of spawning sites and substrates and are more benign environments that are less likely to experiences catastrophic debris torrents post-wildfire that could extirpate populations. References: Miller et al., 2003; Buffington et al. 2004; Wenger et al. 2011; Goode et al. 2013.	Stream reach slope values from the NHDPlus Version 2 website: http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
Length (km<5%) or volume (Vol<5%) <5%	Positive effect. Cumulative length or volume of reaches within a natal habitat patch that are less than 5% slope. Reaches below this slope threshold have low probabilities of experiencing catastrophic debris torrents after wildfires, so larger areas of low slope areas may provide more robust internal refugia and protect bull trout populations from extirpation. References: Sedell et al. 1990; Bozek and Young 1994; Hungr et al. 2005; Cannon et al. 2010; Sedell et al. 2015.	Stream reach slope and historical scenario discharge data from the NHDPlus Version 2 website: http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php and the Western U.S. Stream Flow Metrics website: https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml
Length (km<9°C) or volume (Vol<9°C) <9°C	Positive effect. Cumulative length or volume of reaches within a natal habitat patch that are less than 9°C mean August stream temperature. Reaches below this temperature threshold are more suitable for juvenile bull trout and less so for brook trout, so larger areas with especially cold temperatures may provide internal thermal refugia and preclude wholesale invasions of natal patches by brook trout.	Historical baseline scenarios of stream temperature and discharge data from the NorWeST Regional Database and Modeled Stream Temperatures website: https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html and the Western U.S. Stream Flow Metrics website:

	References: Isaak et al. 2015, 2017b; Wilcox et al. 2018.	https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml
Winter high flow frequency (WHFF)	Negative effect. The number of days during the winter season that high flows exceed the 95% percentile of annual flows through the reaches constituting a bull trout patch. A measure of hydrologic flashiness describing the potential for channel scouring events that could destroy bull trout eggs incubating in stream substrates during the winter. References: Shellberg et al. 2010; Wenger et al. 2010, 2011; Goode et al. 2013.	Historical baseline flow scenario from the Western U.S. Stream Flow Metrics website: https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml
Average flow mass date (AFMD)	Positive effect. The date on which the average center of annual flow mass occurs, measured as the number of days after the start of a standard water year on 1 October. Bull trout patches with later flow dates should benefit juvenile recruitment and population persistence because young fish have more time to grow and may be better equipped to endure large annual snowmelt floods that occur each spring. References: Seegrist and Gard 1972; Elliott 1987, Latterell et al. 1998; Fausch et al. 2001; Wenger et al. 2010.	Historical baseline flow scenario from the Western U.S. Stream Flow Metrics website: https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml
Baseflow index (BI)	Positive effect. The ratio of baseflows to annual total flows. Natal patches with higher baseflow index values may have larger groundwater contributions, exhibit dampened flood variability, and should be more benign and productive environments for bull trout populations. References: Biggs 1995; Wolock et al. 2003; Reiser et al. 2004; Shellberg et al. 2010; Goode et al. 2013.	Base-flow index grid layer for the conterminous United States downloaded from the ScienceBase-Catalog website: https://www.sciencebase.gov/catalog/item/537f6a6fe4b021317a86e394
Road density (RD)[2]	Negative effect. The number of road crossings that intersect a bull trout patch or the length of roads within a portion of a watershed hosting a patch. Road density is potentially detrimental to bull trout as a consequence of increased sedimentation and removal of instream wood, increased hydrologic volatility from more efficient routing of precipitation through basins, greater impedance to fish migration caused by culverts at road crossings, and provision of human access, which historically contributed to overharvest of adult bull trout and introductions of competitor trout species, especially brook trout (*Salvelinus fontinalis*).	Five road density metrics were calculated as described in Appendix D. A composite road layer was developed from multiple sources that included federal (https://www.blm.gov/or/gis/data-details.php?id=17) and state geospatial datasets (Idaho: https://catalog.data.gov/dataset/tiger-line-shapefile-2015-state-idaho-primary-and-secondary-roads-state-based-shapefile; Montana: https://mslservices.mt.gov/Geographic_Information/Data/DataList/datalist_Details.aspx?did={26E71BA8-914E-458B-B2EC-62F22AD06C30}; Nevada: https://www.nevadadot.com/doing-business/about-ndot/ndot-

	References: Bjornn and Reiser 1991; Dunham and Rieman 1999; Baxter et al. 1999; Jones et al. 2000; Trombulak and Frissell 2000; Meredith et al. 2014; Mims et al. 2019.	divisions/engineering/location/geospatial-data; Oregon: https://spatialdata.oregonexplorer.info/geoportal/details;id=12d99bf70d064391b5f487ed6bce4133; Washington: https://www.wsdot.wa.gov/mapsdata/geodatacatalog/)
Riparian canopy trees (RCT)	Positive effect. Riparian canopy classified as the percentage of trees along 1-km reaches that constitute bull trout patches. Higher tree canopy values are associated with larger amounts of instream woody debris and greater habitat complexity that may benefit bull trout. References: Rich et al. 2003; Meredith et al. 2014.	U.S. Forest Service Tree Canopy Cartographic layer derived from the 2011 National Land-use Cover Database. Downloaded from https://www.mrlc.gov/data?f%5B0%5D=category%3Atree%20canopy
Wildfire prevalence (WP)[2]	Positive or negative effect. Proportion of a watershed with a bull trout patch that burned at low, medium, or high severity during wildfires in a recent 10- or 20-year period. Wildfires may depress bull trout habitat occupancy either through immediate, acute effects associated with degraded water quality and temperature spikes or in the first few post-fire years through catastrophic scour and sedimentation during debris torrents. Later, the increase in large woody instream debris from fire-killed trees on adjacent hillslopes may enhance habitat complexity, the increase in sediment can contribute to greater availability of suitable spawning substrates, and the opening of riparian canopies can improve primary and secondary productivity that spur recruitment and growth of salmonids. References: Rieman et al. 1997; Bozek and Young 1994; Dunham et al. 2003, 2007; Hitt 2003; Sestrich et al. 2011; Smith et al. 2011; Luce et al. 2012; Sedell et al. 2015; Lemoine et al. 2020.	Twenty wildfire prevalence metrics were calculated as described in Appendix D. Wildfire perimeters and burn severity information were downloaded from the Monitoring Trends in Burn Severity website: https://www.mtbs.gov/.
Connectivity (C)[2]	Positive or negative effect. Many types of metrics are available for quantifying connectivity, and their specific formulations may translate to either negative or positive effects on bull trout patch occupancy. Generally speaking, however, beneficial effects on patch occupancy are anticipated where connections to other populations are greater due enhanced dispersal that may provide demographic support or permit refounding populations after local extirpations. Conversely, greater connectivity also provides corridors for non-native species invasions. References: Brown and Kodric-Brown 1977; Dias 1996; Dunham and Rieman 1999; Rieman and Dunham 2000; Moilanen and Nieminen 2002; Rich et al. 2003; Fausch et al. 2009.	Sixteen connectivity metrics were calculated based on the sizes and distances of occupied bull trout patches relative to each individual patch in the dataset. Definitions of the metrics are provided in Appendix D.

Brook trout (BKT)[1]	Negative effect. Prevalence of brook trout within a bull trout patch calculated as the percentage of fish survey sites with brook trout. Brook trout invasions are often associated with declines in bull trout populations and occasional extirpations due to non-introgressive hybridization, predation, and competition, although the effect is primarily in small streams. References: Dunham and Rieman 1999; Spruell et al. 2001; Rieman et al. 2006; Warnock and Rasmussen 2013; Isaak et al. 2015; Howell et al. 2016; Wilcox et al. 2018.	Datasets previously published in Buchanan et al. 1997; Isaak et al. 2015; Howell et al. 2018; Young et al. 2017, 2018 and supplemented with interviews of local fisheries biologists.
Adfluvial bull trout (Adfluv)	Positive effect. Presence of lakes or reservoirs downstream from natal patches that host large adfluvial bull trout which migrate upstream to spawn in natal patches. Lentic environments are more productive than lotic habitats for piscivorous bull trout and the presence of migratory fish within local habitat networks may add resilience due to the greater fecundity of larger fish, size-selective mating reducing reproductive wastage with smaller brook trout, and greater ability to find and colonize suitable habitats that are unoccupied. References: Rieman et al. 1997; Ferguson et al. 2019.	Interviews with local biologists and author's knowledge about the study streams was used to code natal patches (0 or 1) to indicate the presence of adfluvial bull trout.
Bull trout (BT)	Response variable. Presence or absence of bull trout within potential natal habitat patches.	Datasets previously published in Buchanan et al. 1997; Isaak et al. 2015; Howell et al. 2018; Young et al. 2017, 2018 and supplemented with interviews of local fisheries biologists.

[1]One of four covariates used in an earlier bull trout patch occupancy model (Isaak et al. 2015).
[2]Different variants of the covariate were considered in a preliminary analysis described in Appendix S4. The two variants with the best predictive performance were selected for use in final model development reported in the text.

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