ANTICIPATED CLIMATE WARMING EFFECTS ON BULL TROUT HABITAT
AND POPULATIONS ACROSS THE INTERIOR COLUMBIA BASIN
(BULL TROUT CLIMATE PROJECT)

Project Summary, Data Analysis and Model Development

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Project Summary

Our approach can be outlined in five general steps: 1) we summarized site level observations of "small" bull trout to identify lower elevation limits of natal habitats across the basin; 2) we summarized mean annual air temperatures for weather stations across the same area; 3) we regressed each set of observations against longitude and latitude (and elevation in the case of temperature) and compared the coefficients in the two regression models to consider whether climate could explain bull trout distributions; 4) we used a GIS to map the area and size distributions of thermally suitable habitat patches based on predicted distribution limits; and 5) we used the GIS to explore changes in distributions, area, and number of suitable habitat patches by elevating lower distribution limits consistent with three levels of warming bounding the range of recent predictions. We constrained our analysis to the potential range of bull trout in the basin following Rieman et al. (1997). We considered suitable patches to be the area of a watershed above the predicted lower distribution limit of small (< 150 mm) bull trout because these individuals are strongly associated with natal habitat and a clear thermal gradient (Dunham and Rieman 1999; Dunham et al. 2003).

Data Analysis and Model Development

Bull Trout Distribution

Observations of the occurrence of bull trout and brook trout Salvelinus fontinalis (an invading species that may displace bull trout) were summarized within 76 streams sampled at multiple sites (along an elevation gradient) throughout the Interior Columbia basin. We obtained observations from two sources: directly from biologists responsible for inventory or monitoring and from published or archived data sets with clearly defined and controlled sampling methods (Platts 1974, 1979; Mauser 1986; Hoelscher and Bjornn 1988; Mauser et al. 1988; Clancy 1993; Adams 1994; Dambacher and Jones 1997; Dunham et al. 2003). Our sample was restricted to the following: streams with bull trout smaller than 150 mm fork length (with the exception of one data set where the closest recorded size break was 170 mm); streams with at least five sample sites distributed across 500 m in elevation; and sites represented by at least 45 m of sampled stream. For one data set we combined observations from groups of three 15-m long sites that were within 60 m of elevation to represent single sites. Elevations were recorded for the mid-point of sites from 1:24,000 scale U.S.G.S. topographic maps.

The analysis was limited to streams where at least two sites without small bull trout occurred below, and at least two sites with small bull trout occurred above, the site with the lowest bull trout observation. We restricted our sample rather than using the larger set of all lowest observations (i.e., bounded or not) because the appropriate model for the latter would require boundary or quantile regression (e.g., Flebbe et al. 2006), essentially forcing the model through the extreme observations. We believe the lower bounds of bull trout distributions among streams vary in

response to temperature and its interaction with other environmental conditions such as the presence of brook trout (Rieman et al. 2006). We assumed that changes in temperature associated with climate could displace other effects (e.g., brook trout would move up in elevation as well) or that similar effects at higher elevation would contribute to similar variability in the lower bound. As a result, regression through the extreme observations would produce an overly optimistic average (i.e., fish at lower elevations) of bull trout habitat use.

Mean Annual Air Temperature

Mean annual air temperature "30-year normals" (i.e., averages for a 30-year period) were used from the period 1961 to 1990 to examine the regional spatial pattern in climate. We obtained records for 191 permanent weather stations distributed throughout the basin from the 1993, 1994, or 1996 NOAA climatological data summaries for each state (e.g., NOAA 1993). We then determined air temperature "normals" by taking the mean annual air temperature at a station in a given year and substracting the "departure from normal" reported for that year and station. We used temperature normals for 1961-1990 to derive estimates appropriate for the period of bull trout sampling and encompassing any decadal-scale variation in climate that might obscure regional patterns observed over shorter periods. All but three of our bull trout distribution observations were from data gathered between 1972 and 1996. The last three observations were from 1999 to 2001. Although we recognized that warming probably occurred over this time (e.g., Hari et al. 2006), we assumed that it had not substantively altered regional patterns and a general association of air temperature with elevation required by our analysis.

Mean annual air temperature was chosen as the simplest measure of climate and its potential effects on the species' distribution. We used the annual mean rather than summer mean because we were uncertain what characteristics of a temperature regime actually influence bull trout. Moreover, ground water temperature is generally correlated with mean annual air temperature (Meisner 1990; Flebbe 1993; Nakano et al. 1996), has been strongly associated with distributions of other chars (Meisner 1990; Flebbe 1993; Nakano et al. 1996), and has been shown to influence survival of embryos and early juvenile growth of bull trout (McPhail and Murray 1979; Baxter 1997). Air temperatures are correlated with stream surface water temperatures (Rahel et al. 1996; BER unpublished data), which have been associated with juvenile bull trout distributions (Dunham et al. 2003) as well.

Models

Multiple linear regression was used to model the lower elevation limit of bull trout as a function of latitude and longitude (both in decimal degrees). Because brook trout may displace bull trout to higher elevations (Rieman et al. 2006), the presence or absence of brook trout also was evaluated as a categorical predictor. First-order interactions were assessed, but were not significant and were excluded from further consideration. Regression parameters were estimated using standard techniques that assumed spatial independence among residuals and were compared to estimates derived from spatial autoregressive techniques (Cressie 1993). Unbiased parameter estimates were obtained using restricted maximum likelihood procedures in the MIXED procedure in SAS2 (Littell et al. 1996). If residual errors were spatially correlated, the autoregressive models would provide the most accurate parameter estimates (Cressie 1993). Comparisons between aspatial and spatial models were made using likelihood ratio tests (Littell et al. 1996).

Diagnostic tests of regression residuals suggested no need for data transformations. Standardized residuals indicated four outlying observations (> 2 SD), which were examined, found to be valid, and retained in the analysis. Cook's distance and DFFIT statistics indicated these observations did not strongly affect parameter estimates. Variance inflation factors < 3 suggested that correlations among predictors did not artificially inflate standard error estimates. Regression models for mean annual air temperature were developed using the same approach as for bull trout distribution limits. Mean annual air temperature was regressed against elevation,

latitude, longitude, and first order interactions. Residuals were normally distributed, but were slightly heteroskedastic. A log transformation of air temperatures exacerbated the problem, so we proceeded with untransformed data. Standardized residuals indicated six outliers, but no observation strongly affected parameter estimates. Variance inflation factors indicated no problems with multicollinearity.

Results Summaries

A raster based DEM was used along with rasterized latitude and longitude coordinates and our regression models to map potential bull trout habitat across the basin. The DEM data were originally referenced to the geographic coordinate system with a cell size of 3 arc seconds and were transformed to the Albers Equal Area coordinate system with a spatial resolution of 90 m. Latitude and longitude coordinates were assigned to each cell in the raster with the same approximate spatial resolution and then input into the bull trout regression equation, along with the DEM data, to characterize each cell as at, above or below, the lower limit of predicted habitat. We converted the raster data to vector format so that cells at the predicted lower limits were delineated by an isopleth. The lower limit was then adjusted upward to create isopleths reflecting an upward shift in elevation with anticipated warming (see below).

Stream lines were derived for the basin from the DEM using TauDEM software (Terrain Analysis Using Digital Elevation Models; Tarboton 1997). We clipped the DEM into 78 USGS 4th level hydrologic unit codes (HUCs) or "subbasins" to reduce the data volume of the resultant GIS stream layers. TauDEM was run for every individual HUC to derive stream lines. We used these "synthetic" stream lines in the analysis because they are spatially co-registered to the DEM and because TauDEM generates a contributing area attribute for the watershed of each stream segment. The digital stream lines were overlain with each isopleth to delineate potential bull trout habitats. We identified watersheds that fell above the isopleth as thermally suitable habitat patches and recorded the area and number of patches.

Distributions and Potential Climate Effects

Potential effects of climate warming were estimated by manipulating the elevation limits of fish distributions over a range bounding the predicted effects of warming in the next 50+ years. We used the regression models and patch derivation procedure to develop the recent or base habitat condition and three predictions of suitable area and patch size frequency distributions. For the base condition, we summarized results based on the bull trout lower limit regression model. We assumed that as warming occurs, lower limits of bull trout will move up in elevation by an amount equivalent to the mean lapse rate of air temperature (average change in temperature for a unit change in elevation) estimated from the temperature regressions. We then estimated new patch areas and numbers as above. We assumed that warming would not alter upper bounds of bull trout distributions because there have been no clear lower thermal limits (upper elevation limits) associated with bull trout distributions, and small stream size appears to be the more important upper constraint in headwater streams (Dunham and Rieman 1999).

Total area of patches and number of patches of selected sizes were estimated. We summarized predictions across the 78 subbasins and within 20 USGS 3rd level HUCs to reduce the complexity of the subbasin pattern. The 3rd level HUCs are formally known as basins, but we refer to these as subregions to avoid confusion with the subbasin and basin designations used previously.

Patterns and anticipated risks with climate change were visualized across the basin we summarized patch sizes for each subbasin. Based on analyses of bull trout occurrence and patch size in the Boise River basin, Idaho (Rieman and McIntyre 1995; Dunham and Rieman 1999), we assumed patches larger than 10,000 ha would support local populations large enough to have a high probability of persistence, while patches less than 5,000 ha would face a substantially higher probability of local extinction. Multiple local populations can help insure

persistence of a larger metapopulation (Hanski and Simberloff 1997) and current guidance for bull trout recovery planning suggests five or more local populations of modest size will be necessary to ensure persistence of the species in most of the larger "core areas" used for planning and management (W. Fredenberg, U.S. Fish and Wildlife Service, personal communication). Core areas are generally consistent with the subbasins we used for our data summary. We defined subbasins with no patches larger than 5,000 ha as high risk and subbasins with five or more patches larger than 5,000 ha, or two or more larger than 10,000 ha, as low risk. Subbasins with an intermediate number of patches were considered at moderate risk.