SENSITIVITY AND VULNERABILITY OF BROOK TROUT POPULATIONS TO CLIMATE CHANGE

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ABSTRACT — Predicting future brook trout *Salvelinus fontinalis* distributions at the population scale under various climate scenarios is of interest to the Eastern Brook Trout Joint Venture. Previous larger scale models have been useful in highlighting the potential threat; however, the predicted air and water temperature errors associated with these models makes predictions of the persistence of individual brook trout populations problematic. We directly measured paired air and water temperatures in watersheds (N = 77) containing reproducing populations of brook trout in Virginia. We found that paired air and water temperature relationships are highly variable among patches but are a useful dataset to classify sensitivity and vulnerability of existing brook trout patches. We developed a classification system using sensitivity and vulnerability metrics that classified sampled brook trout habitats into four categories (High Sensitivity- High Vulnerability (51.9%); High Sensitivity-Low Vulnerability (10.4%); Low Sensitivity-High Vulnerability (7.8%); Low Sensitivity-Low Vulnerability (29.9%). Our direct measurement approach identified potential refugia for brook trout at lower elevations and with higher air temperatures than previous larger scale modeling efforts. Our sensitivity and vulnerability groupings should be useful for managers making investment decisions in protecting and restoring brook trout.

INTRODUCTION

Although no known brook trout *Salvelinus fontinalis* populations have been extirpated because of climate change effects (Hudy et al. 2008), several studies have identified the potential threat of air temperature increases in dramatically reducing the current range of brook trout in the eastern United States (Meisner 1990; Flebbe 1994; Clark et al. 2001; Flebbe et al. 2006). While useful in highlighting the potential threat from increases in air temperature, the errors associated with models using secondary data (predicted air temperatures (PRISM 2007); and predicted water temperature response relative to predicted air temperature) makes predictions of the persistence of individual brook trout populations under various climate change scenarios problematic (Johnson 2003). Models using secondary data often ignore site-specific landscape characteristics that may influence the relationship between air and water temperatures. Predictions of habitat loss based on models that assume a simple positive direct relationship between air and water temperature across all habitats are likely to be overly pessimistic (Meisner 1990; Flebbe 1994; Keleher and Rahel 1996; Rahel et al. 1996; Clark et al. 2001;

Flebbe et al. 2006; Rieman et al. 2007; Williams et al. 2009). Some brook trout habitats may persist even under the most pessimistic climate change scenarios due to localized landscape conditions. Variability in the relationship between water temperature and air temperature can be quantified (Cluis 1972; Pilgrim et al. 1998; Mohseni and Stefan 1999; Isaak and Hubert 2001; Johnson 2003) and effectively used by managers to rank the resistance of individual brook trout populations to various climate change scenarios. Identifying brook trout habitats that are more resistant to air temperature increases is an important step in prioritizing the restoration and conservation work of the Eastern Brook Trout Joint Venture (EBTJV 2006). Our pilot studies and earlier research (Fink 2008) suggest that the relationship between air and water temperature is (1) highly variable at the current brook trout population scale and (2) influenced by local conditions and their interactions (i.e. elevation, aspect, topography shading, riparian cover, latitude, longitude, insolation and ground water sources). The influence of these characteristics at localized scales appears to play a more important role than expected in stream thermal stability (Meisner 1990; Pilgrim et al. 1998; Moore et al. 2005; Wehrly et al. 2007; Fink 2008).

The specific objectives of this study are to (1) quantify the variability in the daily maximum air and daily maximum water temperature responses during the water temperature stress period (July 1 to September 30) for brook trout populations in Virginia and (2) develop a classification system using sensitivity and vulnerability metrics that will be of use to managers in prioritizing their work for brook trout.

METHODS

Study Area, Sample Unit Delineation and Selection

This project includes all habitats with reproducing populations of brook trout within the state of Virginia. Brook trout presence-absence data from the EBTJV (Mohn and Bugas 1980; EBTJV 2006; Hudy et al. 2008) were overlaid on catchments from the National Hydrography Plus (NHD+) dataset (USGS 2008) to produce a dataset of catchments containing reproducing populations of brook trout. Contiguous catchments containing brook trout were then dissolved into individual watersheds or “habitat patches” of reproducing brook trout. Each patch was presumed to be isolated (reproductively) from other patches. A total of 272 patches were found in Virginia. Candidate landscape metrics hypothesized to be important to potential air temperature and water temperature relationships were summarized in a Geographic Information System (GIS) for both the watershed area above the pour point, and the watershed area above the patch centroid (Table 1). The pour point is the intersection of the stream segment in the NHD+ dataset and the most downstream brook trout occupied catchment boundary. The centroid location of the brook trout habitat patch was determined by a GIS algorithm and then snapped to the nearest stream channel (Figure 1). A cluster analysis (Ward’s Method; SAS 2000) was used to group the 272 patches into 9 groups (see table 1 for grouping metrics). We then systematically selected

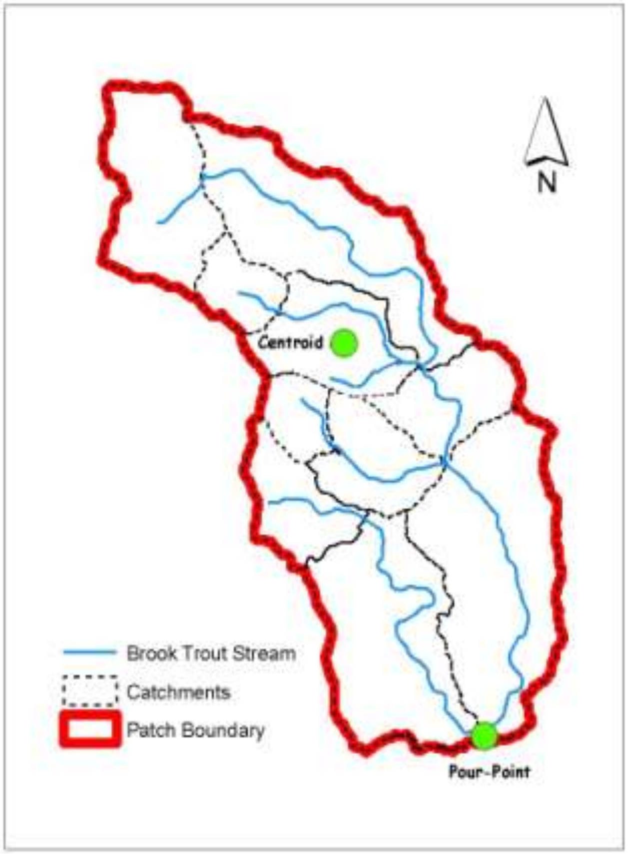

Figure 1. Contiguous catchments containing brook trout were dissolved into “patches” of reproducing brook trout habitat. Paired air and water temperature thermographs were placed at pour point and at the stream section nearest to the centroid to directly measure water temperature responses to air temperatures.

Table 1. Candidate landscape metrics summarized for each patch or watershed above each centroid (sample areas = patch or centroid watershed). Metrics followed by an asterisk (*) were used for the cluster analysis subsampling protocol.

Metric	Units	Source
Sample Area	ha	derived
Riparian Area sample area	ha	derived (100m buffer NHD+)
Total Annual Solar Gain sample area	kWh	Fu and Rich 1999
Total Annual Solar Gain in riparian sample area*	kWh	Fu and Rich 1999
Mean Solar Gain (July 1-September 300) in Riparian (100 m buffer) corrected for the percentage of canopy cover	kWh/30mpixel	Fu and Rich 1999
Mean Annual Solar Gain in riparian sample area	kWh/30mpixel	Fu and Rich 1999
Sample point Elevation*	m	derived
Sample point 30-year Mean Max Temp*	Celsius	PRISM 2007
% groundwater flow in sample watershed *	% of patch	USGS 2003
Mean Canopy Cover in sample watershed	% of patch	USGS 2009
Mean Canopy Cover riparian area of sample watershed	% of patch	USGS 2009
% Forest Area in sample watershed*	% of patch	USGS 2009
Land use Area by Category in sample watershed	ha and % of patch	USGS 2009
Land use Area by Category in sample watershed	ha and % of patch	USGS 2009
Geology Type and category in sample watershed		DMME 2008

50 patches from the 9 groups. In each selected patch we placed two pairs (air and water) of thermographs, one at the patch pour point and one at the centroid. Because of dry stream channels (primarily centroids) and lost or stolen thermographs, we had a complete data set on 77 watersheds (pour points = 43; centroids = 34).

We focused on metrics associated with daily maximum water temperature during the critical period for this study because

(1) increases in air temperature (and presumed increases in water temperature) have the highest probability occurrence in various climate change scenarios (Intergovernmental Panel on Climate Change 2007),

(2) daily maximum water temperature metrics for presence and absence of reproducing populations of brook trout are known (Stoneman and Jones 1996; Picard et al. 2003; Wehrly et al. 2003; Huff et al. 2005; Wehrly et al. 2007) and

(3) we believe lethal water temperature effects from climate change will likely occur first and have an immediate and dramatic effect on existing brook trout populations.

Sampling Protocol

Paired (air and water) thermographs (HOBO Watertemp Pro v2; accuracy 0.2˚C; drift <0.1 annually; Onset Computer Corporation 2008) were placed at the pour point and at the centroid of each sampled patch. All thermographs were set to record every 30 min (Dunham et al. 2005; Huff et al. 2005) from July 1st through September 30th (Stoneman and Jones 1996), thus encompassing the only period when water temperatures are likely to exceed the lethal limit (> 21ºC) for brook trout in Virginia.

Thermographs were calibrated pre and post-deployment following methods summarized in Dunham et al. (2005). Because of the possibility that stream channels may run dry during summer low flow periods, thermographs used to record water temperatures were placed near maximum residual pool depths (Lisle 1987) when possible. A shield was used to reduce direct UV contact with air temperature thermographs (Dunham et al. 2005; Wise et al. 2010).

Metrics

We define sensitivity as the change in the daily maximum water temperature (DMAXW) from a 1°C increase in the daily maximum air temperature (DMAXA). Because this sensitivity varies throughout the DMAXA range we report the median change for each watershed as a single sensitivity metric.

In addition, we developed a standardized vulnerability score for each brook trout habitat patch from the DMAXW values. Duration (number of consecutive days above 21°C), frequency (proportion of days above 21°C) and magnitude (average DMAXW of all DMAXW days over 21°C) for the sample period were standardized ((x-mean)/SD) and the average of the three standardized metrics was used for the final vulnerability score. We view this as the "effective dose" associated with increased water temperature. Combining the sensitivity scores with the vulnerability scores resulted in four classification categories: (high sensitivity-high vulnerability (HS-HV); high sensitivity-low vulnerability (HS-LV); low sensitivity-high vulnerability (LS-HV) and low sensitivity-low vulnerability (LS-LV). The cutoffs used in this classification were: > 0.38 °C high sensitivity, <= 0.38 °C low sensitivity; vulnerability > -0.75 high vulnerability, < -0.75 low vulnerability

RESULTS

The response of DMAXW to a 1°C increase in DMAXA averaged 0.38 °C among all sites and air temperature ranges (Figure 2). However, there was considerable variation. For example a one degree DMAXA increase from 16 to 17 °C averaged a 0.52 °C increase in DMAXW but ranged from 0.13 to 0.98 °C dependent on the sample site. A 1°C increase in DMAXA from 25 to 26 °C averaged (0.35) with a range of 0.10 to 0.82 °C (Figure 2).

Our vulnerability metrics also varied among patches; duration averaged 11.75 d (SD = 17.1; range 0 to 56 d); frequency averaged 23% (SD = 29.0%; range 0.0 to 91.0%) and magnitude above 21°C averaged 0.76 (SD = 0.99; range 0.00 to 3.80). The predicted maximum air temperature from the PRISM (2007) data at the sample location was correlated with the vulnerability metrics (r = 0.55 duration; r = 0.52 proportion; r = 0.49 magnitude) as was the sample location elevation (r = - 0.57 duration; r = -0.56 proportion; r = -0.53 magnitude). Neither the predicted maximum air temperature (r = 0.05) nor elevation (r = -0.06) at the sample locations were correlated with the sensitivity metric. The solar insolation in the riparian area (JUL 1 to SEP 30) corrected for canopy cover was not as highly correlated with the vulnerability metrics (r = 0.13 duration; r = 0.23 proportion; r = 0.20 magnitude) as it was with the sensitivity metric (r = 0.28).

Our sensitivity-vulnerability classification system categorized 51.9% of the brook trout habitat patches as both sensitive and vulnerable (HS-HV) to climate change followed by 29.9% (LS-LV); 10.4% (HS-LV) and 7.8% LS-HV (Figure 3). There were significant differences among the group means for sample point elevation (ANOVA, F = 4.44; df = 73; P < 0.006); sample point predicted maximum air temperature (ANOVA, F = 4.76; df = 73; P < 0.004); the watershed area above the sample points (ANOVA, F = 5.10; df = 73; P < 0.003) and the average solar gain (30 m pixel)(JUL 1 to SEP 30) in the riparian area corrected for canopy cover (ANOVA, F = 4.89; df = 73; P < 0.004). In general HS-HV patches were found at lower elevations, with larger watershed areas and higher solar insolation values than LS-LV patches.

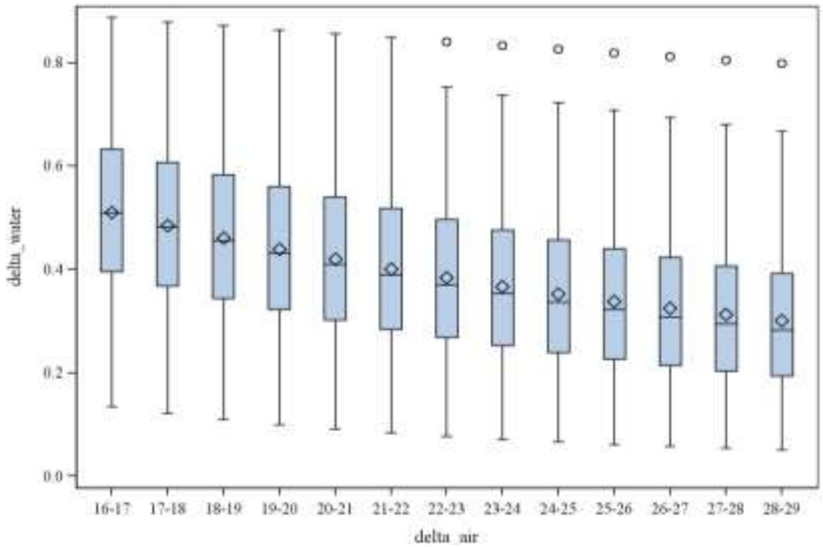

Figure 2. Box plots of the response of daily maximum water temperatures to a 1°C increase in daily maximum air temperature (by one degree bins from 16 to 28 °C) from 77 patches of brook trout habitat during July 1 through September 30, 2009.

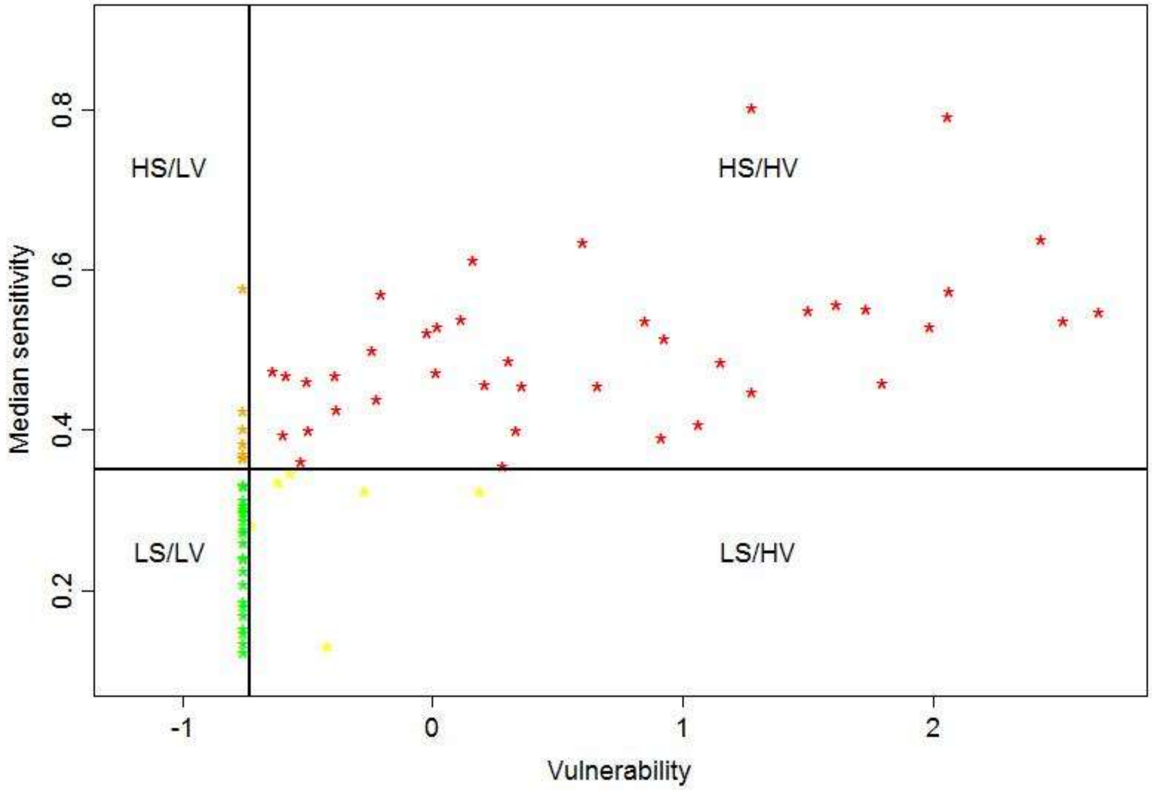

Figure 3. Sensitivity and Vulnerability Classification Chart. (High Sensitivity-High Vulnerability = HS-HV; High Sensitivity-Low Vulnerability = HS-LV; Low Sensitivity-High Vulnerability = LS-HV; Low Sensitivity-Low Vulnerability = LS-LV). See methods for quadrant thresholds.

Discussion

Our direct measurement approach will produce markedly different predictions of future brook trout distributions than models that used secondary data to predict the relationship between air and water temperatures. In most cases, our direct measurement approach identified more brook trout watersheds that are not sensitive and currently not vulnerable to predicted air temperature increases. While typical secondary data sources (maximum air temperature and elevation) used in regional models to predict water temperature were correlated with our sensitivity and vulnerability metrics, our direct measurement approach reduces the chances of error. Air temperature increases from the various climate change scenarios can be applied to the watershed specific air-water temperature relationship curves instead of secondary data model averages to better predict vulnerability to extirpation.

We found considerable variability in our sensitivity metrics among brook trout habitats. Land use metrics such as the interaction of aspect, solar insolation, and canopy cover used in our study may explain the residual errors in these larger models and provide more information for mangers (Fu and Rich 1999; Fu and Rich 2002).

We recommend that when managers make long term planning decisions, such as choosing among populations of brook trout for preserving genetic information or for making investments in habitat restoration, that they develop site specific air-water temperature relationships instead of relying on existing secondary data models.

Combined with our sensitivity-vulnerability classification system this direct measurement approach gives managers a tool to assess potential persistence of individual brook trout habitats under various climate change scenarios. We recommend their use when the potential for costs of an error (either Type 1 or Type 2) from the secondary data models are high.

Although climate change effects other than air temperature (i.e. rainfall, floods, droughts, changes in land cover, spawning times, invasive species, etc.) are important, the low predictability of these metrics (both in magnitude and direction) at this time make it difficult for managers to incorporate this information into the decision making process. Predictions of increasing air temperatures have the highest reliability (Intergovernmental Panel on Climate Change 2007), and we believe that these increases pose the highest risk of change to the current distribution of brook trout. This study is currently being expanded to encompass the entire range of brook trout habitat in the southeastern United States.

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References

Clark, M. E., K. A. Rose, D. A. Levine, and W. W. Hargrove. 2001. Predicting climate change effects on Appalachian brook trout: Combining GIS and individual-based modeling. Ecological Applications 11:161-178.

Cluis, D. A. 1972. Relationship between stream water temperature and ambient air temperature: A simple autoregressive model for mean daily stream water temperature fluctuations. Nordic Hydrology 3:65-71.

DMME (Virginia Department of Mines, Minerals, and Energy). 2008. General Geologic Map of Virginia. Available: http://www.dmme.virginia.gov/DMR3/dmrpdfs/VA%20geol%20map.pdf (July 2010)

Dunham, J., C. Gwynne, B. Reiman, and D. Martin. 2005. Measuring stream temperature with digital data loggers: A user's guide. USDA Forest Service, Report RMRS-GTR-150WWW, Fort Collins, CO.

EBTJV (Eastern Brook Trout Joint Venture). 2006. http://www.easternbrooktrout.org (July 2010)

ESRI. 2009. Solar radiation, extension of spatial analyst tools. Redlands, California

Fink, D. B. 2008. Artificial shading and stream temperature modeling for watershed restoration and brook trout (*Salvelinus fontinalis*) management. Master's thesis. James Madison University, Harrisonburg, Virginia.

Flebbe, P. A. 1994. A regional veiw of the margin: Salmonid abundance and distribution in the southern Appalachian mountians of North carolina and Virginia. Transactions of the American Fisheries Society 123:657-667.

Flebbe, P. A., L. D. Roghair, and J. L. Bruggink. 2006. Spatial modeling to project southern Appalachian trout distribution in a warmer climate. Transactions of the American Fisheries Society 165:1371-1382.

Fu, P. and P.M. Rich. 1999. Design and implementation of the Solar Analyst: An Arcview extension for modeling solar radiation at landscape scales. Proceedings of the 19th Annual ESRI User Conference, San Diego, California. http://esri.com/library/userconf/proc99/proceed/papers/pap867/p867.htr

Fu, P. and P.M. Rich. 2002. A geometric solar model with applications in agriculture and forestry. Computers and Electronics in Agriculture. Volume 37(1-3): 25-35.

Hudy, M., T. M. Thieling, N. Gillespie, and E. P. Smith. 2008. Distribution, status, and land use characteristics of subwatersheds within the native range of brook trout in the eastern United States. North American Journal of Fisheries Management 28:1069-1085.

Huff, D.D., S.L. Hubler, and A.N. Borisenko. 2005. Using field data to estimate the realized thermal niche of aquatic vertebrates. North American Journal of Fisheries Management 25: 346-360.

Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: The Physical Science Basis – Summary of Policy makers. http://www.ipcc.ch/SPM2feb07.pdf

Isaak, D. J., and W. A. Hubert. 2001. A hypothesis about factors that affect maximum summer stream temperatures across montane landscapes. Journal of the American Water Resources Association 37:351-366.

Johnson, S. L. 2003. Stream temperature: Scaling of observations and issues for modelling. Hydrological Processes 17:497-499.

Lisle, T. E. 1987. Using "residual depths" to monitor pool depths independently of discharge. US Forest Service Research Note PSW-394

Keleher, C. J., and F. J. Rahel. 1996. Thermal limits to salmonid distributions in the rocky mountain region and potential habitat loss due to global warming: A geographic information systems (GIS) approach. Transactions of the American Fisheries Society 125:1-13.

Meisner, J. D. 1990. Effect of climate warming on the southern margins of the native range of brook trout, salvelinus fontinalis. Canadian Journal of Fisheries and Aquatic Science 47:1065-1070.

Mohn, L. and P. E. Bugas, Jr. 1980. Virginia trout stream and environmental inventory. Federal Aid in Fish Restoration, Project F-32, final report. Virginia Department of Game and Inland Fisheries. Richmond, Virginia.

Mohseni, O., and H. G. Stefan. 1999. Stream temperature/air temperature relationship: A physical interpretation. Journal of Hydrology 218:128-141.

Moore, R. D., D. L. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. Journal of the American Water Resources Association :813-834.

Onset Computer Corporation. 2009. HOBO U22 Water Temp Pro v2 users manual. Document # 10366-C. http://www.onsetcomp.com/files/manual_pdfs/10366-C-MAN-U22-001.pdf

Picard, C. R., M. A. Bozek, and W. T. Momot. 2003. Effectiveness of using summer thermal indices to classify and protect brook trout streams in northern Ontario. North American Journal of Fisheries Management 23:206-215.

Pilgrim, J. M., X. Fang, and H. G. Stefan. 1998. Stream temperature correlations with air temperatures in Minnesota: Implications for climate warming. Journal of the American Water Resources Association 34(5):1109-1121.

PRISM. 2007. Title. Oregon State University, Corvallis. Available: http://www.prism.oregonstate.edu/. (November 2009).

Rahel, F. J., C. J. Keleher, and J. L. Anderson. 1996. Potential habitat loss and population fragmentation for coldwater fish in the north platte river drainage of the rocky mountinas: Response to climate warming. Limnology and Oceanography 41(5):1116-1123.

Rieman, B. E., D. Isaak, S. Adams, D. Horan, D. Nagel, C. Luce, and D. Meyers. 2007. Anticipated climate warming effects on bull trout habitats and populations across the interior columbia river basin. Transactions of the American Fisheries Society 136:1552-1565.

SAS. 2000. SAS/STAT User’s Guide, Version 8(1). SAS Institute, Cary

Stoneman, C. L., and M. L. Jones. 1996. A simple method to classify stream thermal stability with single observations of daily maximum water and air temperatures. North American Journal of Fisheries Management 16:728-737.

USGS (United States Geological Survey) 2008. The national map seamless server. http://seamless.usgs.gov/website/seamless/viewer.htm. Accessed 24 September, 2008

USGS (United States Geological Survey) 2009. National land cover dataset 2001. USGS, Washington, D.C. Available: www.mrlc.gov. (February 2009).

USGS (United States Geological Survey) 2003. Baseflow index grid for the conterminous United States. USGS, Washington, D.C. Available: http://water.usgs.gov/lookup/getspatial?bfi48grd (February 2009).

Wehrly, K.E., L. Wang, and M. Mitro. 2007. Field-based estimates of thermal tolerance limits for trout: Incorporating exposure time and temperature fluctuation. Transactions of the American Fisheries Society 136:365-374.

Wehrly, K. E., M. J. Wiley, and P. W. Seelbach. 2003. Classifying regional variation in thermal regime based on stream fish community patterns. Transactions of the American Fisheries Society 132:18-38.

Williams, J. E., A. L. Haak, H. M. Neville, and W. T. Colyer. 2009. Potential consequences of climate change to persistence of cutthroat trout populations. North American Journal of Fisheries Management 29:533-548.

Wise, L. M., B. A. Trumbo and M. Hudy. 2010. Determining Drift in Electronic Temperature Sensors Used in Climate Change Modeling. James Madison University undergraduate research (unpublished).