Assessing Climate Change Effects on Aquatic Ecosystems in the Crown of the Continent: Implications for Adaptive Management

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Agency Partners: Crown Mangers Partnership (USA and Canada), U.S. Geological Survey, The University of Montana, Flathead Basin Commission, Glacier National Park, U.S. Forest Service, U.S. Fish & Wildlife Service, Montana Fish, Wildlife & Parks, Confederated Salish and Kootenai Tribes, Montana State University.

Thematic Categories: Aquatic integrity (primary), habitat connectivity, species vulnerabilities, data integration, climate change, and partnerships.

Project Summary: Climate change is impacting freshwater ecosystems worldwide, yet the potential and realized effects on aquatic ecosystems and resources in the Crown of the Continent Ecosystem (CCE) are poorly understood. The continued research described herein builds on an existing climate change and transboundary research program evaluating physical (thermal, hydrologic, geomorphic) and biotic (invasive species) effects on foodwebs (rare macroinvertebrates), native salmonids (threatened bull trout and westslope cutthroat trout), and habitats in the Transboundary Flathead River system and CCE. The project will integrate downscaled and regionalized climate models with riverscape data, fine-scale aquatic species vulnerability assessments, population genetic data, and remotely sensed riparian and aquatic habitat and connectivity analyses. Results will identify populations and habitats most susceptible to climate change, prioritize conservation options in response to or in anticipation of climate change and other cumulative stressors (e.g., habitat loss and invasive species), and develop an Aquatics Adaptation Plan for the Transboundary Flathead and CCE.

Need for Project: Climate change poses a serious threat to natural resources, biodiversity, and ecosystem services in the United States (Botkin et al. 2007), especially in the Rocky Mountain Ecoregion (Hauer et al. 1997; Hauer et al. 2007). Increasingly, natural resource managers require scientifically robust and regionally relevant information on climate change and associated variability to assess key impacts and species sensitivities to future climate conditions. The CCE is experiencing warmer winters, less snowpack, increased fires, increased stream temperatures, and more variable hydrologic regimes (Pederson et al. 2010). These climate-induced environmental changes are likely to result in significant changes in the distribution, abundance, phenology, and genetic diversity of many aquatic species (Parmesan and Yohe 2003), particularly inland salmonids (Haak et al. 2010; Isaak et al. 2012; Muhlfeld et al. In-review) and rare invertebrates (Muhlfeld et al. 2011). Therefore, understanding the potential impacts of climate change on aquatic ecosystems is needed to develop and implement pro-active conservation, recovery, and management programs at regional and watershed scales in the GNLCC.

The CCE is considered one of the largest, most pristine, and biodiverse ecosystems in North America (UNESCO 2010). In the heart of the CCE is the Transboundary Flathead Watershed, a significant portion of which forms Waterton-Glacier International Peace Park, a World Heritage Site and Biosphere Reserve (Fig. 1). The Transboundary Flathead originates in British Columbia and flows into Montana and is considered one of America's wildest and most biodiverse river systems. Its water quality is pristine, it harbors abundant and diverse aquatic life, and it has long been recognized as a range-wide stronghold for two hallmark threatened fish species, the bull trout and the westslope cutthroat trout (Hauer and Muhlfeld 2010). As such, UNESCO (2010) recently concluded: *"The Flathead is regarded as one of the last of America's remaining wild rivers and of global ecological significance…and recognizing the clear evidence for ecological and environmental stress under changing climatic regimes, specific programs of management and associated monitoring and research should be developed to combat climate change impacts. Adaptive management strategies should give emphasis to enhancing the resilience and capacity of wildlife and plants in adjusting to changing environmental conditions".*

As the CCE undergoes rapid change, there is an urgent need to conduct vulnerability assessments for those aquatic species and habitats most susceptible to climate change. Further, there is a need to develop population and habitat models and link them to adaptation strategies in order to best direct conservation efforts in the face of climate change and other existing stressors (e.g., land-use and invasive species).

Fig 1. The CCE and Transboundary Flathead Watershed.

Overarching Goals: The project described herein is part of an ongoing research program to assess aquatic integrity in the Transboundary Flathead Basin of Canada and USA. We propose to continue our regional assessment of aquatic ecosystem processes, population vulnerabilities, and the modeling of potential responses to both climate change and human-induced change as the basis for adaptive planning and management of aquatic ecosystems in the GNLCC, using the Transboundary Flathead Ecosystem as a case example. Indeed, the Transboundary Flathead and the ongoing research, policy applications, and political complexities has many of the elements specifically coherent with all four conservation goals of the GNLCC; thus, the proposed activities described herein can be viewed as a unique opportunity to set a strong pace for future GNLCC development.

Objectives: We propose to build on our ongoing research through the following specific objectives:

(1) ***Conduct vulnerability assessments of native salmonids and stream invertebrates***: Develop vulnerability assessments for native threatened salmonids and stream macroinvertebrates in the Transboundary Flathead and CCE. Produce spatially explicit distribution, abundance, and genetic diversity models of aquatic biota at multiple trophic levels. Apply new and existing techniques for combining downscaled, regionalized climate models with spatially explicit vulnerability and habitat data to predict effects of climate change on connectivity, distributional shifts, gene flow, genomic integrity, demographics and persistence of bull trout, westslope cutthroat trout, and rare macroinvertebrate populations.

(2) ***Linking Remote Sensing Data of Fluvial Habitat to Hydrologic and Geomorphic Change Analyses:*** Integrate spatially explicit hydrogeomorphic, thermal and habitat models of critical stream and riparian habitats of the Transboundary North Fork (developed in previous years of this program) with vulnerability assessments and connectivity models and the thermal and flow tolerance assessments. Use NetMap tools to understand, visualize, discuss, and integrate outcomes.

(3) ***Develop an Aquatics Adaptation Plan for the Transboundary Flathead:*** Develop an aquatics adaptation plan for the Transboundary Flathead Ecosystem (Canada and USA) to identify conservation options in response to climate change and other important cumulative stressors (e.g., habitat degradation and fragmentation, and invasive species).

Methods and Approaches

Overview of Linkages and Approaches - This project will dovetail with our previous GNLCC funding, as well as NPS, USFS, USGS Pacific Northwest Climate Science Center, USGS, and NSF funded projects. These other projects are currently underway in the Transboundary Flathead Basin, and while not duplicating the effort described here, they strongly couple with the above objectives, thus leveraging efforts into a more comprehensive mission. Specifically, we have developed hydrologic, thermal, and geomorphic models that link climate effects to specific stream reaches throughout the Transboundary Flathead and CCE, and have further developed biological models that predict trout population attributes from past, current and future stream habitat conditions. When coupled with our proposed stream corridor/hydraulics habitat analysis and thermal imagery data, we will have direct linkage between the downscaled climate models, the habitats that lead to specific thermal and hydrologic regimes, and the geospatial analysis of the distribution and abundance of those habitats. We will use these climate models and predictions of future climate conditions based on downscaled data (S. Hostetler, USGS) to predict changes in habitat distributions and risks posed to trout and key-indicator invertebrate populations throughout stream networks of the Transboundary Flathead Basin for a range of plausible climate scenarios. These data will be combined with new genetic data of the two fish species using spatially explicit 'demogenetic' modeling approaches to project effects of climate change on trout. All these data and modeling tools will be used to develop a Transboundary Flathead Adaptation Plan for aquatic species.

Objective 1: Vulnerability assessments of native salmonids and stream invertebrates: Vulnerability assessments are key for assessing potential impacts of environmental change on species and ecosystems, thereby informing adaptation planning and management decisions. Understanding the interactions between climate shifts and existing stressors is critical for identifying which species and ecosystems are likely to be affected by projected changes and why they are likely to be vulnerable. This component of our research will provide a better understanding of how climate change will influence native salmonids and aquatic invertebrate populations, their persistence and vulnerability to climate change, and the adaptability of species to thermal and hydrologic change.

Our previous (see our GNLCC-funded publications below) and proposed ongoing GNLCC-funded research will: 1) link species vulnerability assessments with climate and habitat model outputs; 2) use spatially explicit temperature and flow models to identify habitat change; and 3) provide future casting scenarios that allow analysis and synthesis of management actions that may enhance sustainability of stream foodwebs. Specifically, we will use fine-scale submodels using high resolution (22 m) data in a spatially explicit framework to examine risk associated with increasing temperatures, modified hydrologic regimes, disturbance events, habitat modification, and invasion of non-native species in the Transboundary Flathead and CCE.

In 2014, we propose to develop a high-resolution, spatially explicit *daily* stream temperature model for the entire CCE (Fig. 2). This will be the first *daily* stream temperature model developed within the GNLCC, and it will allow more accurate assessments of species vulnerabilities throughout their entire life cycle across multiple hydrophysiographic regions. Recently, we worked with CMP partners to develop and maintain a comprehensive stream temperature monitoring network (>900 sites; Fig. 2) throughout the CCE. These data will be used to develop a high-resolution spatial-temporal statistical model to predict daily stream temperatures under historic, current (1980–2013) and future climate conditions at a 30 m resolution. The model, which corrects for spatial and temporal autocorrelation, is empirically based using correlations between observed stream temperatures and climatic, geomorphic, and geographic predictor variables. Model inputs include: (1) *High-resolution climatic surfaces*, including air temperature (800m) as the driving climatic covariate in the model, along with precipitation, solar radiation, and snow water equivalent (NASA Daymet; 1km) to describe landscape processes at the regional scale; (2) *Groundwater-surface water exchange* is characterized using a combination of covariates (alluvial valleys, hydrogeology); and (3) *Glacier and lake effects*, which are estimated using empirical data. Results will be used to identify thermal and hydrologic exceedances for aquatic species under climate change scenarios (e.g., Jones et al. 2013).

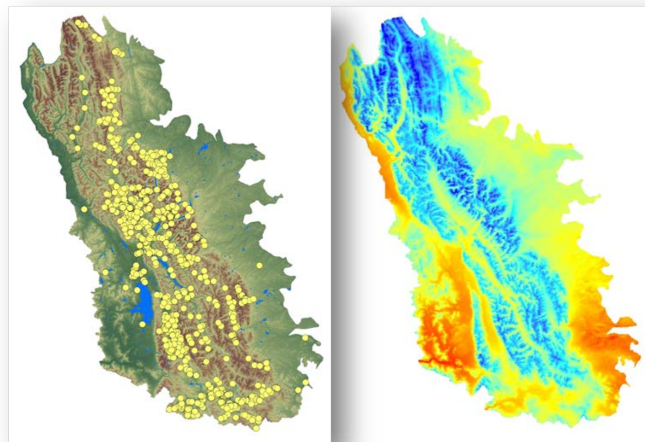

Fig 2. Stream temperature sites (left) and air temperature surfaces (right).

Understanding how climate change will influence population persistence, connectivity (both demographic and genetic), genetic integrity and expansion of invasive species is increasingly urgent for management and restoration of aquatic biota in the CCE. We have developed novel techniques for combining downscaled spatial climate data with population abundance, distribution, and genetics data to predict effects of climate change on connectivity and persistence of bull and cutthroat trout populations in the Flathead system and CCE. For example, the following are products from our 2013 GNLCC funding:

- Muhlfeld et al., (In-revision). Invasive hybridization is accelerated by climate change in a threatened species. ***Nature Climate Change***

Here, we combined long-term genetic monitoring data with high resolution climate and stream temperature predictions to evaluate how recent climate warming has influenced the spatiotemporal spread of human-mediated hybridization between threatened native westslope cutthroat trout and non-native rainbow trout (Fig. 3). During a 30-year period of accelerated warming, hybridization spread rapidly and was strongly linked to climate-induced decreases in spring precipitation and increases in summer stream temperature. This study shows that rapid climate warming can exacerbate interactions between native and non-native species through invasive hybridization, which could spell genomic

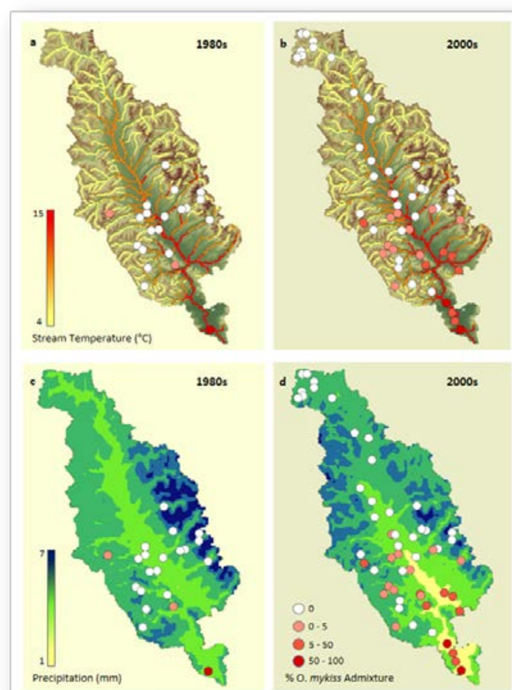

Fig 3. Spatiotemporal spread of hybridization linked to climatic drivers.

extinction for many species. Results will be used in our Adaptation Plan for the Flathead system (see Objective 3).

- Landguth, Muhlfeld et al., (In-press). Combining demographic and genetic factors to assess population vulnerability in stream species. ***Ecological Applications***

We developed a novel modeling framework for aquatic systems that integrates spatially-explicit, individual-based, demographic and genetic (demogenetic) data with environmental variables (e.g., water temperature, flow, habitat complexity, physical barriers) to assess population vulnerability of aquatic species. This tool allows researchers and managers to evaluate the impacts of stressors on genetic diversity and demography of populations through time.

In 2014, we will use these and other products (see previous GNLCC proposals and publications below) to produce spatially explicit vulnerability assessments for incorporation in our habitat analyses (i.e., NetMap; Objective 2) and ultimately the Transboundary Flathead Aquatics Adaptation Plan (Objective 3). Results will help guide conservation and restoration strategies for protection of the most threatened stream segments and populations at risk in the Transboundary Flathead and CCE.

Objective 2: Linking Remote Sensing Data of Fluvial Habitat to Hydrologic and Geomorphic Change Analyses: Fundamental to understanding the distribution and abundance of species and their potential response to climate change is quantifying the biophysical space (habitat) that promotes successful growth and reproduction in different species or life stages. Physical and biological attributes of riverscapes vary in time and space and can interact to determine the quantity and quality of specific habitat. Sufficient habitat, as well as complexity of habitat, are not only required for species-specific persistence, but also biodiversity across a landscape. However, habitats are constantly changing within a dynamic landscape and feedback mechanisms are often complex and nonlinear, ultimately making habitat for different species in a landscape difficult to define.

We have recently developed the technology for collecting and processing airborne remotely sensed data (ARS) for the purpose of habitat evaluation and analysis (Hauer and Lorang 2004). Specifically, airborne remotely sensed data are collected with an ultra-high resolution multispectral imagery system deployed from an aircraft. We have collected the multispectral imagery data for riparian and water cover classification among Montana (2011) and British Columbia tributaries (2012). To date, we have completed quantification of specific river and tributary habitats in the Transboundary Flathead, including: 1) quantification of stream channel (e.g., riffles, runs, pools) and riparian (e.g., forest, shrub and wetland complexes) habitat; 2) geomorphic setting of subsurface habitats of low and high hydraulic conductance of ground water (e.g., the hyporheic zone); and 3) thermal refugia and winter ice cover. We have conducted vulnerability assessments based on hydrologic and geomorphic drivers of habitat change across the significant bull trout spawning and rearing tributaries of the Transboundary Flathead River in the US and Canada. We now need to link these physical, biological and thermal habitat markers to the distribution and productivity and critical life histories of bull and cutthroat trout.

The Transboundary Flathead and CCE encompass a complex mix of federal, state, tribal, and private lands in the US, and federal, provincial and private lands in Canada. As such, natural resource managers must deal with a complexity of land-uses and conservation planning at multiple scales (watershed, drainage, and landscapes). In 2013, the GNLCC provided financial support to extend NetMap into the BC portion of the Transboundary Flathead for use in our Aquatics Adaptation Plan. NetMap is a community-based watershed science system consisting of uniform databases and shared analysis tools for watershed planning, restoration, and conservation at multiple spatial scales (Benda et al. 2007). The application of NetMap allows spatially explicit identification of impacts from various land-uses, such as roads and associated surface erosion, in support of restoration planning and prioritization for improving watershed processes and stream habitats for aquatic organisms. Our objective for 2014 is to link trajectories of habitat change (i.e., persistence, spatial change, change in frequency) with the regionally downscaled climate models within NetMap to understand the processes of habitat change. Ultimately, this will be used to develop a long-term diagnosis of how hydrologic, thermal and geomorphic change in the Transboundary Flathead system influence critical habitats for aquatic biodiversity.

Objective 3: Develop an Aquatics Adaptation Plan for the Transboundary Flathead: Adaptation planning has emerged as a powerful management tool to help people prepare for and cope with the current and projected impacts of climate change and other stressors on ecosystem dynamics and services. Developing comprehensive and effective adaptation strategies, therefore, requires understanding the potential impacts and uncertainties associated with climate change, and assessing the vulnerability of populations, species, and ecosystems to climate change and existing stressors. As such, climate change adaptation planning is rapidly becoming the optimal method by which conservationists and natural resource managers can develop approaches that minimize risk for increasingly different and uncertain future changes.

In 2013, the CMP adopted a general framework to develop an Aquatics Adaptation Plan for the Transboundary Flathead, focusing on cumulative impacts of climate change, invasive species, and habitat loss/degradation (Fig. 4). The Adaptation Plan focuses on three principles: (1) building *resistance* to climate-related stressors; (3) enhancing *resilience* to change; and (3) anticipating and facilitating ecological transitions that reflect changing environmental conditions (Glick et al. 2011). We propose to use our vulnerability assessments and spatially explicit tools (described in Objectives 1-2; also see previous proposals, reports and project publications below) to develop an Aquatics Adaptation Plan for the Transboundary Flathead (FY2013-15). The adaptation strategy is driven by the conservation and management goals identified in the 2010 MOU between Canada and the USA, including cultural, biological and economic components. The adaptation framework (Fig. 4;) involves five elements: (1) identifying conservation targets; (2) assessing vulnerability to climate change and existing stressors; (3) identifying and prioritizing management options; (4) risk assessment of management options; and (5) implementing management options.

Fig 4. Transboundary Aquatics Adaptation Plan adopted by the CMP.

We will use our spatially explicit models of stream temperature (daily and seasonal) and flow to forecast changes in the suitability of bull trout and westslope cutthroat trout populations and habitats over the course of their entire life cycle. The physical and bioclimatic model predictions will be coupled with our new genetic and demographic vulnerability mapping tool (Landguth et al. 2012; Landguth, Muhlfeld et. al. 2014) that uses a demogenetic vulnerability index in combination with simulations (above) to identify subpopulations at risk given a riverscape scenario of current or future river conditions. Finally, we will assess the relative vulnerability of populations and habitats to the combined effects of climate change, habitat alterations, and invasive species using NetMap. The plan will be used to identify which species and systems are most likely to be impacted by ongoing and projected climate change and why they are likely vulnerable. This information can be used to prioritize and implement effective conservation strategies for the entire aquatic ecosystem via adaptation planning. Elements 3-5 will involve other technical, financial, and policy-level considerations (including chance of success) and will require obtaining input from multiple stakeholders and resource management agencies in the Transboundary Flathead Ecosystem (e.g., CMP). Results may be used to: a) develop pro-active, on-the-ground conservation programs to reduce existing stressors; b) manage ecosystem function and diversity; c) provide refugia and improve habitat connectivity and complexity; d) monitor populations and habitats (physical, biological – including invasives); and e) implement management and restoration programs to build resistance and resiliency for adaptation.

Deliverables and Timeline:

- High resolution climate data sets produced by our regional climate models (FY2012-14)
- High resolution (<1m) habitat classification and analysis of selected and representative stream reaches (from alpine to valley floor, FY2012-14)
- Fine scale species distribution modeling with supportive data with scenarios for agency conservation strategies and conservation efforts (FY2012-FY2014)
- Physiological responses of aquatic organisms to changes in flow and temperature (FY2011-14)
- Vulnerability assessments for bull trout and cutthroat trout in the Transboundary Flathead (FY2012-14)
- Development of a daily stream temperature model for the CCE (FY2014)
- Link habitat assessments with NetMap (FY2014)
- Completion of an Adaptation Strategy for the Transboundary Flathead (FY2015)
- Data sharing in the GNLCC [Data will be made available to resource managers dealing with aquatic systems, including the Crown Managers Partnership, USGS, FWS, USFS, BLM, provincial, state management agencies, and private organizations (e.g., Trout Unlimited, Nature Conservancy) (ongoing)
- Workshops to present the results and decision support tools to managers and provide hands-on training (2015)
- Multiple peer reviewed publications of the study (ongoing, see publication list below)

Statement of compliance: Both Principal Investigators had read GNLCC Information Management, Delivery, and Sharing Standards and agree to comply with those standards if the proposal is selected.

Literature Cited:

2011-2014 Project Publications (funded by the GNLCC):

- **Muhlfeld** et al. *In-revisio*n. Invasive hybridization is accelerated by climate change in a threatened species. *Nature Climate Change*.
- **Giersch, J.J, C. C. Muhlfeld et al.** In-review. Rediscovery of a rare alpine stonefly, *Zapada glacier*, threatened by climate change in Glacier National Park, Montana.
- Landguth, E.L., **C.C. Muhlfeld** et al. *In-press*. Combining demographic and genetic factors to assess population vulnerability in stream species. ***Ecological Applications***.
- **Jones, L.A., C.C. Muhlfeld**, L.A. Marshall, B.L. McGlynn, and J.L. Kershner. 2013. Estimating Thermal Regimes of Bull Trout and Assessing the Potential Effects of Climate Warming On Critical Habitats. *River Research and Applications*. DOI: 10.1002/rra.2638
- Isaak, D., **C.C. Muhlfeld**, A. Todd, R. Al-Chokhachy, J. Roberts, J. Kershner, K. Fausch, S. Hostetler. 2012. The Past as a Prelude to the Future for Understanding 21st Century Climate Effects on Rocky Mountain Trout. *Fisheries* 37:542-556.
- Landguth, E.L., **C.C. Muhlfeld** and Gordon. Luikart. 2012. CDFISH: an individual-based, spatially explicit, landscape genetics simulator for aquatic species in complex riverscapes. *Conservation Genetics Resources* 4:133-136. DOI: 10.1007/s12686-011-9492-6.
- **Muhlfeld, C.C**., J. J. Giersch, **F.R. Hauer**, G.T. Pederson, G.L. Luikart, D.P. Peterson, C.C. Downs, and D.B. Fagre. 2011. Climate change links fate of glaciers and an endemic alpine invertebrate. *Climatic Change* 106:337-345.
- H.G. Billman, J.J. Giersch, K.M. Kappenman, **C.C. Muhlfeld**, M. Webb. *In-press*. Thermal tolerance of meltwater stonefly nymphs from an alpine stream in Waterton-Glacier International Peace Park, Montana, USA. *Freshwater Science*.
- Schweiger, E. William, Isabel W. Ashton, **C.C. Muhlfeld**, Leslie A. Jones, and Loren L. Bahls. 2011. The distribution and abundance of a nuisance native alga, *Didymosphenia geminata*, in streams of Glacier National Park: climate drivers and management implications. *Park Science*. 28(2):88-91
- Amish, S.J., P.A. Hohenlohe, S. Painter, R.F. Leary, **C.C. Muhlfeld**, F. Allendorf, and G. Luikart. Westslope cutthroat and rainbow trout species-diagnostic SNP assays developed from next-generation RAD sequencing. *Molecular Ecology Resources* 12:653-660.
- Paul A. Hohenlohe, Mitch D. Day, Stephen J. Amish, Michael R. Miller, Nick Kamps-Hughes, Matthew C. Boyer, **Clint C. Muhlfeld**, Fred W. Allendorf, Eric A. Johnson, Gordon Luikart. 2013. Genomic patterns of introgression in rainbow and westslope cutthroat trout illuminated by overlapping paired-end RAD sequencing. *Molecular Ecology*. doi: 10.1111/mec.12239

For more information, please visit our GNLCC website: http://greatnorthernlcc.org/features/climate-change-aquatic-ecosystems.

References

Benda, L., D. Miller, K. Andras, P. Bigelow, G. Reeves, and D. Michael. 2007. NetMap: A new tool in support of watershed analysis and resource management. Forest Science 53:206-219.

Botkin, D.B. et al. 2007. Forecasting the effects of global warming on biodiversity. Bioscience 57:227.

Glick, P., B.A. Stein, and N.A. Edelson, editors. 2011. *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment.* National Wildlife Federation, Washington, D.C.

Haak, A.L., J.E. Williams, D. Isaak, A. Todd, C. C. Muhlfeld, J.L. Kershner, R. Gresswell, S. Hostetler, and H. Neville. 2010-*In review*. The potential influence of changing climate on the persistence of western trout and grayling. USGS Open File Report, Reston, Virginia, USA.

Hauer, F. R., J. S. Baron, D. H. Campbell, K. D. Fausch, S. W. Hostetler, G. H. Leavesley, P. R. Leavitt, D. M. McKnight, and J. A. Stanford. 1997. Assessment of climate change and freshwater ecosystems of the Rocky Mountains, U.S. and Canada. *Hydrologic Processes* 11:903-924.

Hauer, F. R. and M.S. Lorang. 2004. River regulation, decline of ecological resources, and potential for restoration in a semi-arid lands river in the western USA. *Aquat. Sci.* 66:388–401.

Hauer, F. R., J. A. Stanford and M.S. Lorang. 2007. Pattern and process in northern Rocky Mountain headwaters: Ecological linkages in the headwaters of the Crown of the Continent. Journal of the American Water Resources Association: 43(1) 104-117.

Hauer, F.R. and C.C. Muhlfeld. 2010. Compelling science saves a river valley. *Science* 327: 1576.

Isaak, D., C.C. Muhlfeld, A. Todd, R. Al-Chokhachy, J. Roberts, J. Kershner, K. Fausch, S. Hostetler. 2012. The Past as a Prelude to the Future for Understanding 21st Century Climate Effects on Rocky Mountain Trout. *Fisheries* 37:542-556.

Jones, L.A., C.C. Muhlfeld, L.A. Marshall, B.L. McGlynn, and J.L. Kershner. 2013. Estimating thermal regimes of bull trout and assessing the potential effects of climate warming on critical habitats. *River Research and Applications*. DOI: 10.1002/rra.2638

Landguth, Erin L., Clint C. Muhlfeld and Gordon. Luikart. 2012. CDFISH: an individual-based, spatially explicit, landscape genetics simulator for aquatic species in complex riverscapes. *Conservation Genetics Resources*. 4:133-136.

Lorang, M. S. Whited, D. C. Hauer, F. R. Kimball, J. S. and Stanford, J. A. (2005), Using airborne multispectral imagery to evaluate geomorphic work across floodplains of gravel-bed rivers. *Ecological Applications*, 15, 1209-1222.

Luikart, G., P.R. England, D. Tallmon, S. Jordan, and P. Taberlet. 2003. The power and promise of population genomics: from genotyping to genome typing. *Nature Reviews Genetics*, 4:981- 994.

Muhlfeld, Clint C., S. Thorrold, T.E. McMahon, and B. Marotz. 2012. Estimating trout movements in a river network using strontium isoscapes. *Canadian Journal of Fisheries and Aquatic Sciences* 69:906-915.

Muhlfeld, Clint C., J. Joseph Giersch, F. Richard Hauer, Gregory T. Pederson, Gordon Luikart, Douglas P. Peterson, Christopher C. Downs, and Daniel B. Fagre. 2011. Climate change links fate of glaciers and an endemic alpine invertebrate. *Climatic Change* 106:337-345.

Muhlfeld, Clint C., Leslie Jones, Daniel Kotter, William J. Miller, Doran Geise, Joel Tohtz, and Brian Marotz. 2012. Assessing the impacts of river regulation on native bull trout (*Salvelinus confluentus*) and westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) habitats in the upper Flathead River, Montana, USA. *River Research and Applications* 28:940-959.

Muhlfeld, Clint C., Steven T. Kalinowski, Thomas E. McMahon, Mark L. Taper, Sally Painter, Robb F. Leary, and Fred W. Allendorf. 2009. Hybridization rapidly reduces reproductive success of a native trout in the wild. *Biology Letters* 5:328-331.

Muhlfeld, Clint C., Thomas E. McMahon, and Durae Belcer. 2009. Spatial and temporal dynamics of spawning between native westslope cutthroat trout (*Oncorhynchus clarkii lewisi*), introduced rainbow trout (*O. mykiss*), and their hybrids. *Canadian Journal of Fisheries and Aquatic Sciences* 66:1153-1168.

Muhlfeld, Clint C., Thomas E. McMahon, Matthew C. Boyer, and Robert E. Gresswell. 2009. Local-habitat, watershed, and biotic factors in the spread of hybridization between native westslope cutthroat trout and introduced rainbow trout. *Transactions of the American Fisheries Society* 138:1036-1051.

Muhlfeld, Clint C., and Brian Marotz. 2005. Seasonal movement and habitat use by sub-adult bull trout in the upper Flathead River system, Montana. *North American Journal of Fisheries Management* 25:797-810.

Muhlfeld, Clint C., Steve Glutting, Rick Hunt, Durae Daniels, and Brian Marotz. 2003. Winter diel habitat use and movement by subadult bull trout in the upper Flathead River, Montana. *North American Journal of Fisheries Management* 23:163-171.

Pederson, G.T., L.J. Graumlich, D. B. Fagre, T. Kipfer, and C.C. Muhlfeld. 2010. A century of climate and ecosystem change in western Montana: what do temperature trends portend? Climatic Change 98:133-154.

Parmesan C., Yohe G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421:37-42.

UNESCO. 2010. Report of the Reactive Monitoring Mission: UNESCO World Heritage Centre, International Union for Conservation of Nature/Waterton-Glacier International Peace Park, 2009.