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A Decision-support System for Assessing the Impact of Fire Management on Threatened and Endangered Species

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Abstract

Historically, wildfire was an important agent of change in landscapes across the western United States. Fires of varying magnitudes and extents contributed to a mosaic of dynamic landscape conditions. For the past century, fire management that focuses on fire suppression has effectively altered the composition of many vegetation communities across the landscape. Fire management and other landuse practices associated with natural resource use, agriculture, and residential development have changed the complexity of terrestrial landscapes. Aquatic systems have not been exempt from these changes: alterations in disturbance processes on the landscape have changed inputs into the stream environment, and practices such as stream cleaning have reduced the capacity of streams to build complex habitats. Road and dam construction have reduced connectivity among quality stream habitats for aquatic dependent species. Despite all these changes and challenges, populations of imperiled salmonids continue to survive. While the abundance and distribution of native aquatic species is much reduced, they persist in areas where suitable habitat exists and is accessible. It is part of the mission of many federal and state land management agencies to work toward a sustainable balance between ecological needs and other uses of the land. In this project, we have expanded and improved tools and techniques that make it easier for managers to consider the ecological and geomorphic effects of fire on aquatic systems. We have developed new applications that model the effect of fire on wood inputs, fine sediment, and stream temperature for the Wenatchee River watershed. We have developed models of Bull Trout and spring Chinook Salmon at landscape scales that allow us to begin to predict the potential effect of fire on the habitats necessary for the long-term persistence of these species. By considering in greater detail the connections between landscape processes and in-stream condition, we offer a landscape-scale perspective that has the potential to inform management regarding approaches to fire management that enhances aquatic habitat.

Background and Purpose

The effect of fire on ecological and geomorphic processes is a critical issue in the management of western forests. Land management at a riverscape scale spans watershed divides and includes ecologically meaningful boundaries such as watersheds, as well as human-imposed management frameworks such as land ownership. How to adapt management of forests and fire to enhance and re-establish ecological function in aquatic systems is not well understood (Gresswell 1999). Fire management has important short- and long-term implications for landscape structure and in-stream habitat conditions. A century of management focused on fire suppression has changed the frequency, intensity, and spatial extent of wildfires. Changing the disturbance processes that fostered habitat complexity throughout western riverscapes has also changed in-stream habitat. Including aquatic issues of habitat quality, stream network connectivity, and fish population resilience in fire management plans offers land managers the opportunity to broaden the goals of fire-suppression and fuels treatment activities (Bisson et al. 2003; Dunham et al. 2003). There is much to learn about the specific effects of fire on in-stream conditions and the resultant effects on fish population persistence. The long-term persistence of native aquatic species requires complex and connected habitats that may only be attainable by changing aspects of the current fire-management paradigm.

When considering effects of fire and fire management on fish and aquatic ecosystems, it is necessary to consider both the physical environment (habitats, water quality) and the biology, including adaptive strategies, of the fish. Key factors that determine the response of a particular stream fish population to fire and other disturbances include: 1) the magnitude and duration of the disturbance event; 2) the potential response of the watershed of interest to fire; 3) the size of suitable habitat patches for the fish species of interest and the degree to which they are connected within the landscape; and 4) the variety and flexibility of life-history attributes of the fish population of interest. Recognition and the integrated assessment of these factors are essential for anticipating the consequences that potential disturbance regimes pose for T&E fish species.

Salmonid populations have generally been viewed as isolated entities whose persistence is largely dependent on the quality of the local environment. However, emerging evidence suggests that the resilience of these populations is also highly dependent on the distribution and abundance of suitable habitat patches and population centers in the surrounding landscape. Stream salmonids are properly viewed as metapopulations (interacting group of populations; Dunham et al. 2002). Metapopulations tend to evolve in dynamic landscapes, where the suitability of a given habitat patch varies over time, sometimes catastrophically, but where favorable patches are always present somewhere because of the asynchronous nature of disturbances. Recovery of populations in disturbed areas occurs by means of the migration of fish from surrounding suitable patches (Rieman and Dunham 2000). Decreasing connectivity among patches reduces the likelihood of persistence in dynamic landscapes (Groom and Schumaker 1993).

Population response to specific disturbances can be species-dependent. In general, species with narrower habitat requirements are more vulnerable to disturbances than habitat generalists (Dunham et al. 2003). Generalists are better able to use to a range of environmental conditions than are specialists. This is particularly true at small spatial scales and in highly fragmented landscapes, where habitat patches are isolated from surrounding patches. Species with complex and flexible life histories have a greater capacity to respond to and recover from disturbances than those with simpler and more rigid life-histories.

Salmonids have adapted to the dynamic riverscapes of the Pacific Northwest through phenotypic plasticity, as is evident in their diverse life histories (Rieman and Dunham 2000; Reeves et al. 1995). Disturbances such as fire provide the mechanism for the delivery of habitat-forming materials to stream channels through debris flows (Benda et al. 2003; Bigelow et al. 2007; Burton 2005). Fires open the forest canopy, providing different opportunities for regeneration and thereby creating a matrix of complex vegetative communities on the landscape. The complexity of stream habitats reflects the complexity of the landscape.

Native stream fishes throughout the western United States have been classified at risk of extinction because of low or declining numbers. Federal land managers are increasingly required to address regulatory requirements and considerations for these species before, during, and following wildfires. This is a daunting task because of the glaring lack of guidance and analysis tools that leave managers with few options for identifying effects of fuels and fire management on aquatic habitat, and even fewer for anticipating effects on endangered fish populations. However, current scientific literature examining fire effects on hydro-geomorphic processes integrated with ecological attributes of the species of interest is sufficient to provide managers with decision-support tools to make on-the-ground, site-specific recommendations for fuels treatment and other land-management activities in the context of pre- and post-fire management planning.

In this project, we specifically sought to develop geospatial tools and population-scale fish models that address three key issues:

1. What fire and fuel management activities can be successfully implemented while maintaining T&E fish populations and their associated habitats?
2. Where on the landscape can fuel management activities be planned to maintain key aquatic habitats and fish populations?; and
3. How can habitats be sustained across broad landscapes that experience fire, particularly in areas that have experienced increased fuel loads from past fire suppression?

In this project report, we will present preliminary findings and responses to these questions which can provide new and integrated guidance to forest managers.

Study Location and Description

Study area

This study focused on the Wenatchee River watershed in central Washington and the associated national forest, the Wenatchee-Okanagan National Forest. The watershed encompasses 3,550 km^2 (1,371 square miles) of north-central Washington and drains a portion of the eastern slopes of the Cascade Range. The Wenatchee River watershed is an area of active wildfire. A large number of wildfires of varied intensity and spatial extent have been documented over the past 30 years in this drainage (Figure 1). The Wenatchee River watershed is contained within the Interior Mixed-conifer Ecoregion. The historic fire regime in this dry forest area was characterized by high-severity fires occurring at 0- to 35-year intervals, and stand-replacing fires occurring every 200+ years (Kennedy and Fontaine 2009).

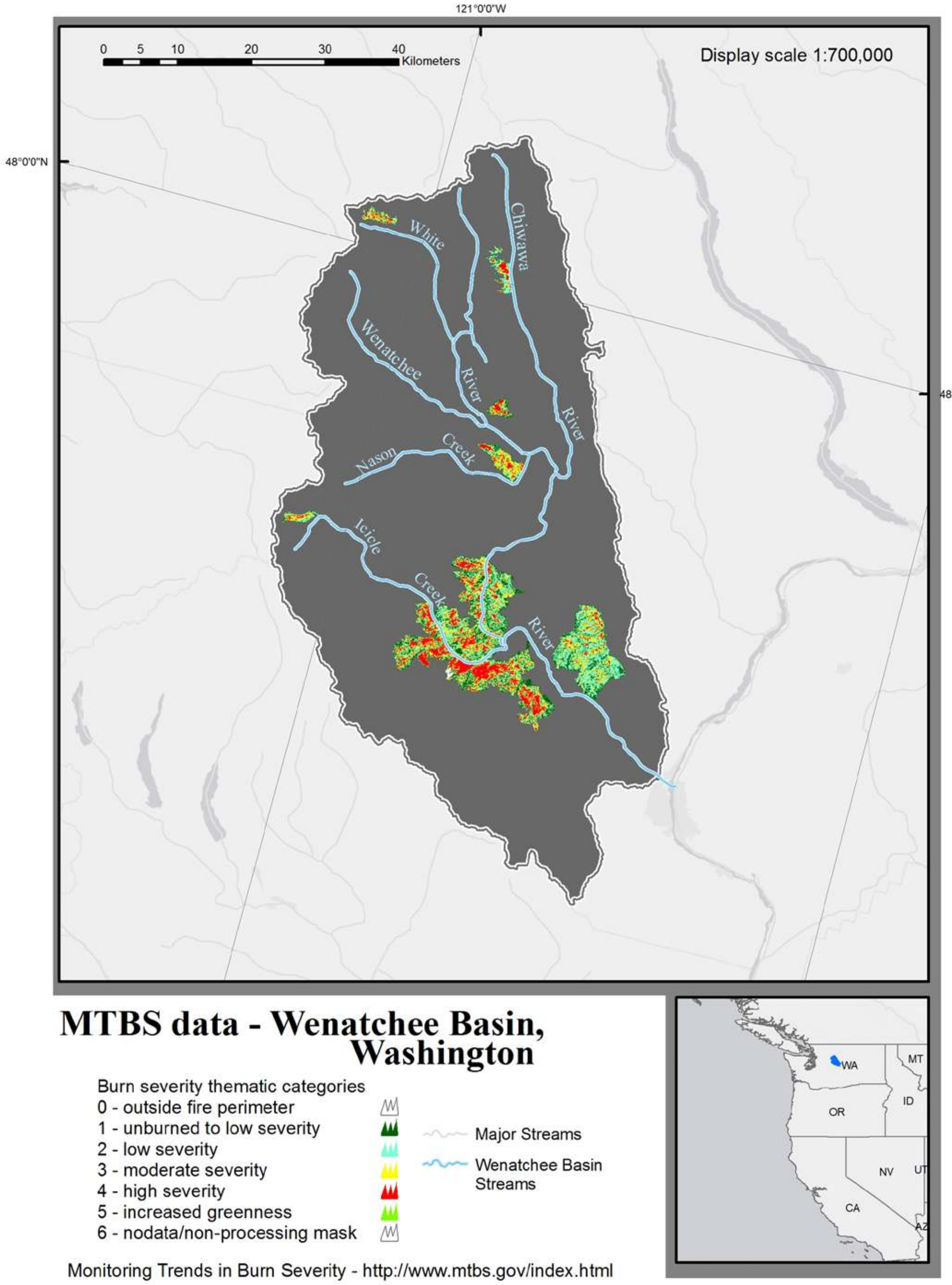


Figure 1. Locations of all documented fires between 1980 and 2011 for the Wenatchee River basin, Washington.

Although multiple geologies underlie the region, glaciation was a primary shaping agent for the current landscape topography and river-channel form.

Higher-elevation areas are characterized by heavy precipitation (381 cm [150 inches] annually) that generally occurs in the form of snow during the winter. In contrast, lower-elevation areas are relatively arid, with minimal precipitation (8.5 inches [21.6 cm] or less annually) and maximum summer temperatures between 95°F and 100°F (35°C and 37.8°C) (Salmon, Steelhead, and Bull Trout Habitat Limiting Factors 2001). The Wenatchee River watershed is home to several fish species that are federally listed under the Endangered Species Act as endangered (Upper Columbia River summer Steelhead, anadromous *Oncorhynchus mykiss*; Upper Columbia River spring Chinook Salmon, *O. tshawytscha*) or threatened (Upper Columbia River Bull Trout, *Salvelinus confluentus*) (Salmon, Steelhead, and Bull Trout Habitat Limiting Factors 2001).

Key Findings

Exploration of the effect of fire on fish habitat in fire-prone systems has direct application to forest management. We developed two sets of landscape-scale models and three new geospatial applications that facilitate modeling and prediction for spring Chinook Salmon and Bull Trout in the Wenatchee River watershed. We sought input from project scientists, local ecologists, and fire managers at the Wenatchee-Okanagan National Forest in order to make our models relevant to those who may ultimately use them on the ground.

Predicting the physical effects of fire on stream channels

Geospatial tools and applications that describe the potential short-term and long-term consequences of fire on aquatic habitat were unavailable before this project. Two applications using tools that were developed for this project are currently available online through NetMap (www.netmaptools.org). One application predicts the potential delivery of fine sediments to streams as a result of fire. The other predicts the delivery of potential habitat-forming dead trees into streams as a result of fire. NetMap (Benda et al. 2007) is an open-source platform designed to model processes affecting aquatic systems. A third application was developed that predicts the potential effect of fire on water temperature within the Wenatchee River watershed. These three applications facilitated fish population model development and allowed for the characterization of the physical effects of fire in the aquatic environment at landscape scales. They have great potential for use and application beyond the modeling work that we describe in this report. We describe these applications in greater detail before explaining how we used them in the fish habitat modeling portion of the project.

Fine sediment

One consequence of fire that can have immediate effects on aquatic habitat quality is associated with increased stream sediment. Fine sediment destabilized by fire and delivered to stream channels through overland erosion and landslides has the potential to reduce egg-to-parr (Burton 2005) and juvenile survivorship. Landslides and debris flows can reduce the quality and quantity of habitat for all life stages, particularly in the short term. An important application developed for this project predicts the potential contribution of fine sediment to be delivered to stream channels as a result of fire. The tools for each step in the application are available for download from the NetMap website (www.netmaptools.org).

The application that predicts delivery of fine sediment to aquatic systems synthesizes data from several sets of widely available information. Fine-sediment delivery from shallow failures post fire is predicted using a topographic index that combines slope steepness and hillslope form (planar, convergent, divergent) and is called ‘generic erosion potential’ or ‘GEP’ (Miller and Burnett 2007). The GEP is created from available digital elevation models, such as the 10-meter national elevation dataset. The GEP index is referenced to an estimated basin annual sediment yield (t/km^2/yr). For example, if the basin average sediment yield is 100 t/km^2/yr, the range of GEP values across the basin will represent spatial variation in sediment yields from 10 to 1000 t/km^2/yr. Geospatial data describing soil textures (NRCS-SSURGO; Soil Survey Staff, Natural Resources Conservation Service 2011) are used to translate predicted sediment yields to volumes of sand-size particles that could enter streams. The GEP-predicted erosion rates, including sand yields, are multiplied by the predicted flame length (from FlamMap, Finney 2006) to derive an estimation of post-fire erosion potential, including the sand fraction (Figure 2, a, b). The pre-fire and post-fire predicted sediment yields are contrasted to create a percent increase in the volume of sand in channels (Fig. 2, c).

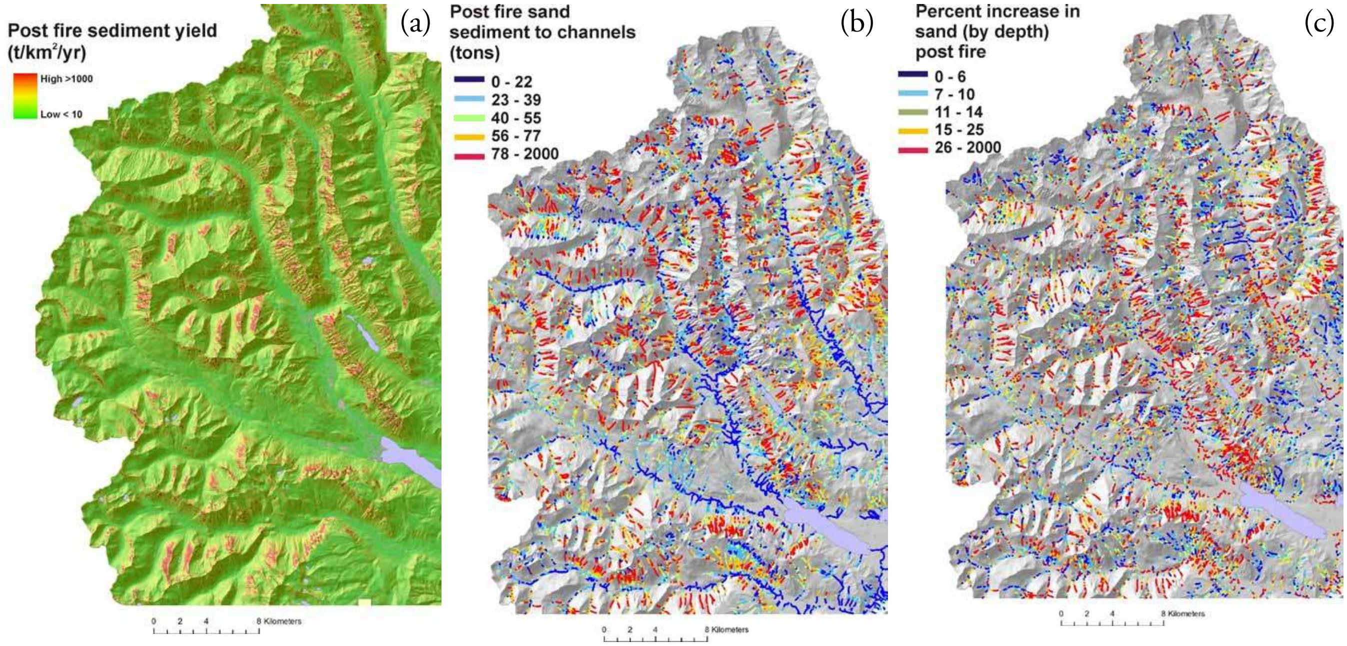


Figure 2. (a) Post-fire sediment yield is based on generic erosion potential, estimated average annual sediment yields, and soil textures; (b) Post-fire fine sediment yields are converted to yields of sand-size particles in streams using information on soil texture. The difference between pre-fire erosion and sediment yield conditions with post-fire sediment yields (in terms of sand load) is used to calculate a percent increase in sand (depth) in streams following fires (c). Post-fire erosion (shallow landsliding) is estimated using a topographic index in conjunction with predicted fire intensities.

Application— Predicting changes in sediment yield at specific stream reaches as a result of fire is the core utility of this application, which we used to model changes in sediment with regard to spawning habitat and egg survival of spring Chinook Salmon. An advantage of this application is that it can be used with readily available spatial datasets, and can be used as part of a larger suite of geospatial tools that are currently available through NetMap. In post-fire environments, forest roads may also contribute to impacts on the aquatic environment. Roads can divert drainage following fires because of increased surface runoff due to lower infiltration post-fire. Increased road-related slope failures or road-surface erosion could occur. NetMap contains a suite of tools for predicting the relationship of forest roads to hillslope failure potential, debris-flow potential, road drainage diversion and road-surface erosion. While the GEP approach to hillslope erosion used in this project is separate from the other road erosion tools available in Netmap, they may be used in concert to explore the potential effect of fire on road sedimentation rates. Many forests already use NetMap tools to model characteristics of the stream environments when planning for conservation, restoration, or other forest treatments. They are also using the tools in the context of “minimum roads analysis”.

Large wood

For the past several decades, forest managers have worked to enhance the complexity of stream habitat through restoration projects that put large wood into streams. Wood in stream channels provides a fundamental building block for stream habitat development and complexity. Over longer time frames (decades), fire has the potential to positively influence in-stream habitat by increasing tree mortality. Fire-killed trees are then delivered to the stream channel as a result of toppling, debris flows, or other mass-transport events. An important application developed for this project predicts the potential amount of fire-killed trees that may be available for stream habitat as a result of fire. A tool that predicts reach-scale wood recruitment at a watershed scale will be available for download from the NetMap website (www.netmaptools.org) by October 2012 (presently there is a reach-scale wood recruitment tool available).

The wood recruitment tool developed for this project predicts the effect of fire on wood supply to streams based on LEMMA forest cover data (Landscape Ecology, Modeling, Mapping, and Analysis: http://www.fsl.orst.edu/lemma/). We used live-stem density to determine the number of potential conifer and hardwood trees that could become snags. Flame length (from FlamMap, Finney 2006) was used to determine potential percent mortality of trees (Table 1). By combining the number of standing trees with predictions of mortality, an estimate of wood that would be available as input into streams was predicted (Figure 3).

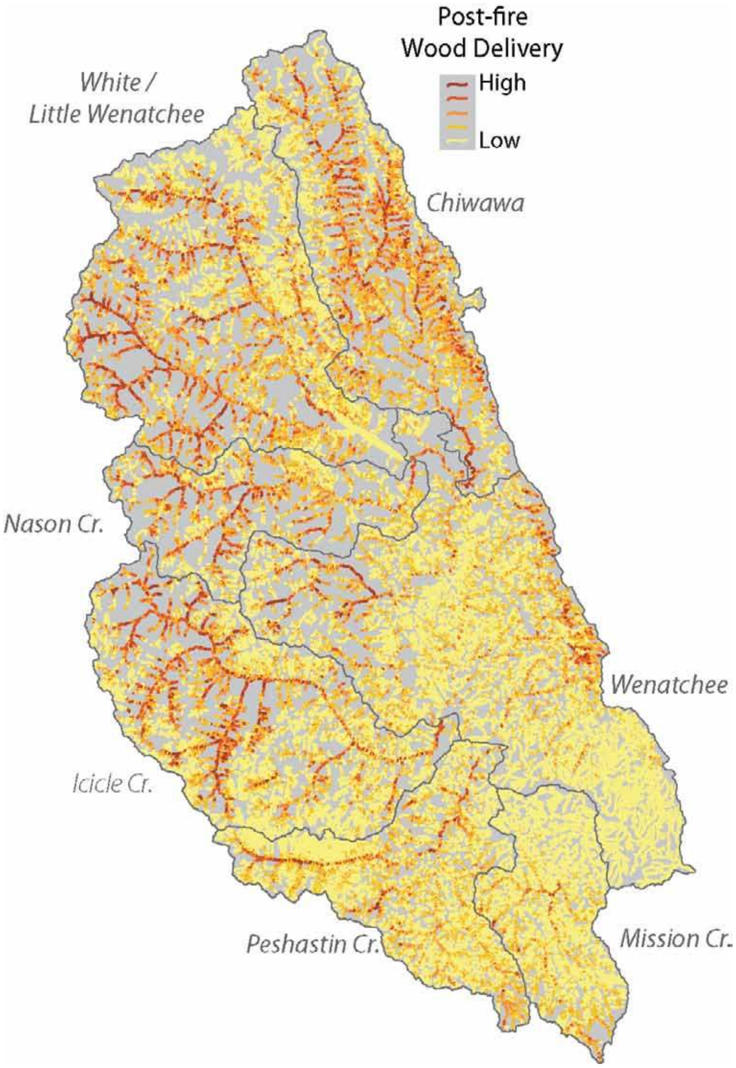


Figure 3. Wood delivery to streams post-fire.

Table 1. Potential mortality of trees under different levels of fire severity. Fire severity is interpreted from predicted flame length.

Fire severity (flame length)	% Mortality
Low (< 4 ft)	10
Medium (4-6 ft)	32.5
High (6-8 ft)	57.5
Very high /severe (>8-20 ft)	85
Severe /crown fire (> 20 ft)	100

Application—The importance of large wood in creating complex stream habitat is well understood. National forests in the West allocate millions of dollars to enhancement of stream habitat through restoration projects that add wood to streams. This geospatial application has the potential to give managers information regarding the natural recruitment potential of habitat-forming large wood to specific stream reaches throughout entire watersheds. Such comprehensive assessments of the potential of the landscape to provide structural wood to stream reaches have not been available before. This type of watershed-scale assessment allows managers and biologists to assess entire forests and determine those locations that may most benefit from in-stream wood placement projects, or from fire events. They can determine which areas lack naturally occurring structural wood and will need placement of large wood structures to enhance stream habitat complexity. They can also identify those areas with high potential for naturally occurring source wood that will become available as a result of fire. Such locations may benefit from management that allows or encourages fire to occur.

NetMap's wood recruitment tool can also be used to evaluate the effects of forest thinning in riparian stands. It can be used to assess the effects of buffers on wood recruitment. In the absence of buffers, the tool can predict what proportion of the wood in streams will be eliminated by riparian thinning. The wood recruitment tool also contains a function for calculating what proportion of the thinned trees should be directionally felled (into the stream) to offset any loss of instream wood by riparian thinning. Thus, NetMap's wood recruitment tool can be used to plan riparian thinning as well as to concurrently plan stream restoration, through the placement of wood in channels.

Stream temperature

The effect of landscape disturbances on in-stream water temperature is of critical concern to forest managers. Fire alters the thermal regime through changes in processes such as surface composition, vegetation, and riparian cover (Dunham et al. 2007). Rather than simply modeling peak, mean, or low stream temperatures for a year, our focus was on the thermal environment throughout an entire year. The thermal setting of the environment is linked to metabolism and growth of fishes (Neuheimer and Taggart 2007). Changes in the thermal regime throughout the year that may be caused by the alteration of landscape processes (such as those caused by fire) have the potential to influence the growth and survival of stream fishes (Bisson and Davis 1976; McCullough 1999) (Figure 4).

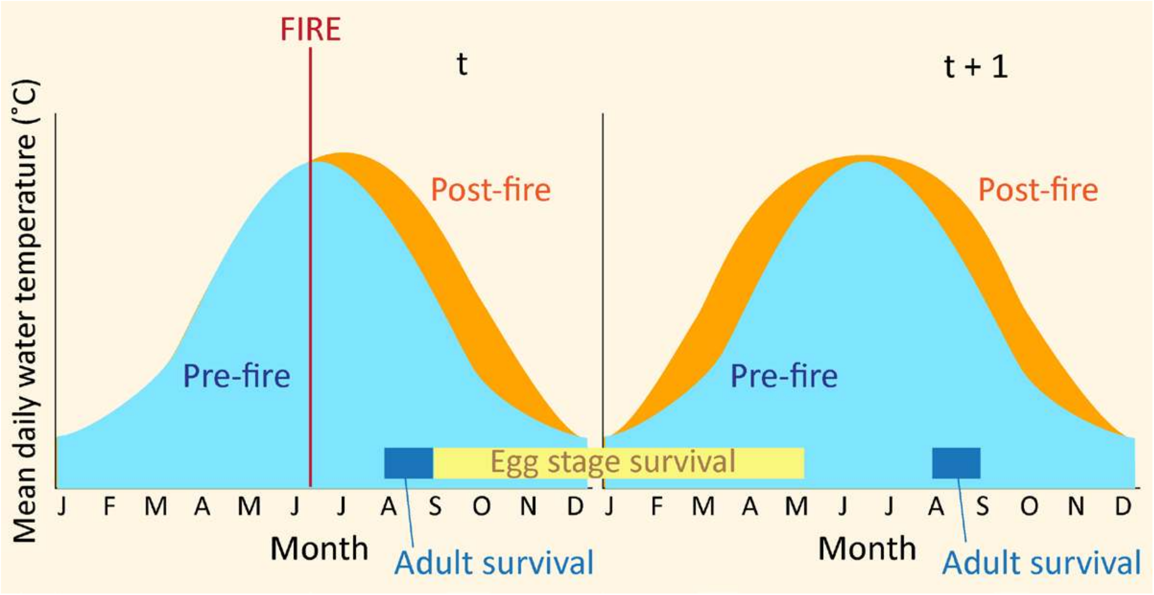


Figure 4. Potential post-fire effect on daily water temperature estimates throughout the year (t = year 1; t+1 = year 2).

Using remotely sensed datasets, we developed relationships that predict the effect of fires of differing intensities and spatial extents on ground temperature. This was done by first developing a way of modeling in-stream temperatures. To accomplish this, we acquired data from the MODIS sensor, at 1-km^2 resolution. These datasets consist of 8-day composites of land surface temperature (LST) for 2001-2010, and are spatially and temporally continuous. Stream temperature data was acquired from a variety of sources including the Wenatchee-Okanagan National Forest and NOAA. Fifty sets of temperature data representing stream conditions from 2001 through 2010 were assembled. Regression was used to relate surface temperature to water temperature. Results indicated that LST functioned well as a predictor of in-stream temperature in the Wenatchee River watershed (Figure 5).

Figure 5. Predicted in-stream temperature based on land surface temperature (LST) and actual water temperatures.

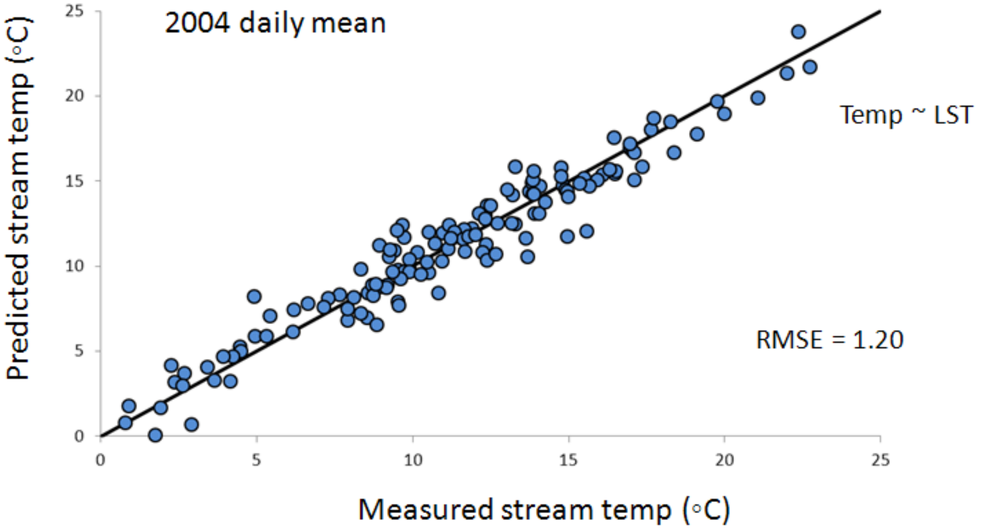
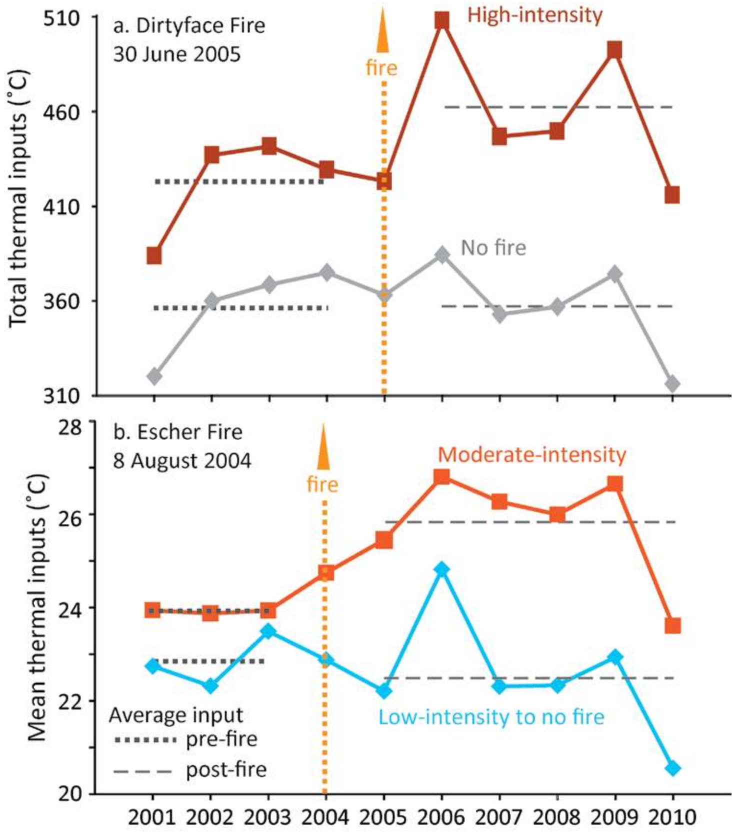


Figure 6. Difference between pre- and post-fire thermal condition during the period of juvenile fish growth (April 1 through September 30). (a) Total thermal inputs pre- and post-fire in a pixel affected by high-intensity fire and in another pixel with no fire. (b) Mean of thermal inputs in a pixel that experienced moderate-intensity fire and in another with no fire.



Records of fire events and intensities in the Wenatchee National Forest over the past three decades were acquired from the Monitoring Trends in Burn Severity Program (MTBS) website (Figure 1). The seven mapped fires that occurred within the Wenatchee River watershed between 2001 and 2008 (the years that correspond with the MODIS dataset) were used to compare land- surface temperature with fire intensity at the scale of 1-km^2 pixels. To summarize changes in the thermal regime during critical time periods for the growth of juvenile fish, we summarized the thermal inputs into the stream environment during the growing season (April 1 – September 30). Differences among the total thermal inputs throughout the growing season (Figure 6a) and the mean of thermal inputs during this time (Figure 6b) indicate that there are differences in stream temperature over time among pixels categorized with low-, moderate-, or high-intensity fire.

The estimated daily change in temperature post-fire for each fire intensity level (low, moderate, and high) was used to predict the potential effect of fire for every pixel across the landscape (Figure 7, example of high-intensity fire prediction). This was combined with the most probable fire intensity for the location (using FlamMap projections, Finney 2006) to generate a map of the predicted effect of fire on stream temperature throughout the Wenatchee River watershed.

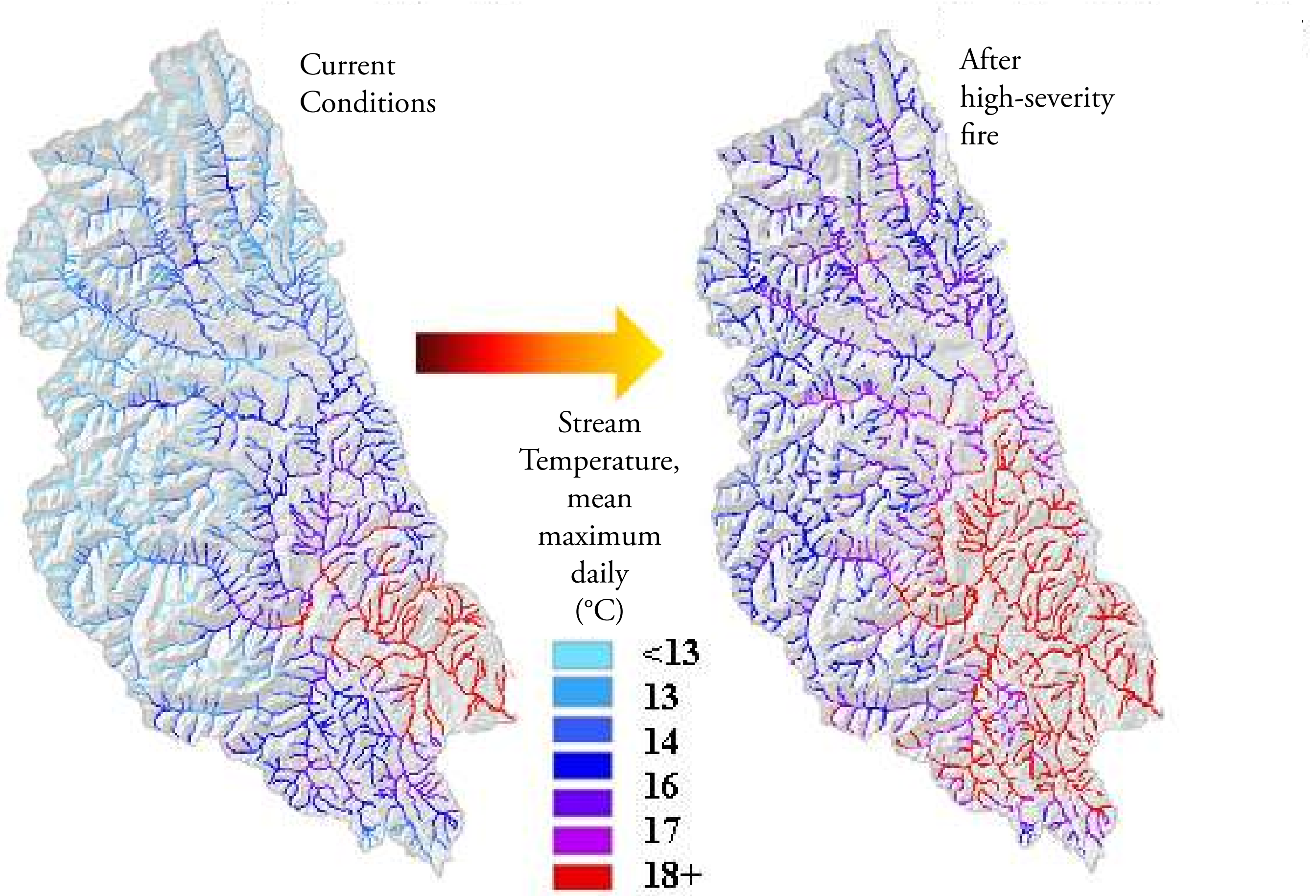


Figure 7. Ten-year mean max daily stream temperature for the Wenatchee River watershed under current conditions assuming that a high-severity fire affects every pixel in the watershed.

Application—The effect of landscape disturbance on stream temperature is an important concern for forest managers and fish biologists. We have developed a technique that predicts the effect of fire on stream temperature at a reach scale using relationships between field-collected stream temperature data and remotely sensed land-surface temperature at a local scale. This technique provides a broader perspective on the effect of fire on the stream environment than simple peak, mean, or low temperatures by modeling temperature at 8-day increments. This robust technique provides an important insight into the effect of disturbance on stream temperature throughout an entire watershed and offers managers the opportunity to develop comprehensive maps of stream temperature throughout the year.

Fish habitat vulnerability to fire

Forest managers are asked to balance a diverse set of conditions on the landscape, including habitat protection and enhancement for endangered species. Landscape modeling tools that predict the effect of fire on terrestrial habitat are available and have supported habitat-based planning for terrestrial species (Agar et al. 2007). The geospatial tools that predict the potential effect of fire on instream habitat condition are an innovation. Our preliminary modeling work with Bull Trout and spring Chinook Salmon habitat in the Wenatchee River watershed offers land managers two different conceptual approaches for considering population viability, and integrates the use of the readily available geospatial tools developed for this project. These models identify locations within the Wenatchee River watershed where spring Chinook Salmon or Bull Trout populations may be most resilient to the most probable fire severity. These models are firmly rooted in concepts of habitat connectivity at multiple spatial scales for all lands within the Wenatchee River watershed.

Bull Trout

Populations of native Bull Trout are distributed throughout the Wenatchee River watershed. Documentation of habitat requirements for these endangered fish typically focuses on water temperature. The objective of this modeling work was to map Bull Trout habitat suitability throughout the Wenatchee River watershed, to use fire model output to predict changes in habitat suitability for Bull Trout post-fire, and to estimate the vulnerability of habitats and populations to fire.

Two spatial extents were used for this analysis: the stream reach and the patch. Stream habitat characteristics were assessed at the reach scale. Reaches were approximately 200 meters in length and calculated using the FLoWS extension in ArcGIS (http://www.nrel.colostate.edu/projects/starmap/flows_index.htm). The contributing upslope area directly perpendicular to the reach was identified as referred to as the reach contributing area or RCA. RCAs were used to quantify terrestrial processes, such as fire intensity, that may affect local in-stream habitat conditions.

Because persistence of any population distributed in a dendritic stream system depends on the connectivity among sub-populations, we included a larger "patch" scale. Patches are important because they allow for the designation of sub-populations and can be used to quantify important concepts such as internal and external connectivity.

Due to the dependence of Bull Trout on cold water conditions, and the paucity of empirical data documenting distribution of Bull Trout in the Wenatchee, we chose to test four different habitat patch scenarios based on maximum temperature as a limiting factor. We identified the downstream most extent of maximum temperature to identify a patch. We included four temperature limiting patch scenarios in our analysis (max temperature of 17°C, 16°C, 15°C and 14°C), because of uncertainty in absolute temperature limitations for Bull Trout (Selong et al. 2001). With a maximum temperature of 17°C, patches of suitable habitat were larger than patches identified with max temperature of 16°C, 15°C, or 14°C (Figure 8). Greatest isolation and fragmentation of patches was associated with colder maximum temperatures. Potential effect of fire and patch connectedness were explored for each of these four temperature-based patch delineations.

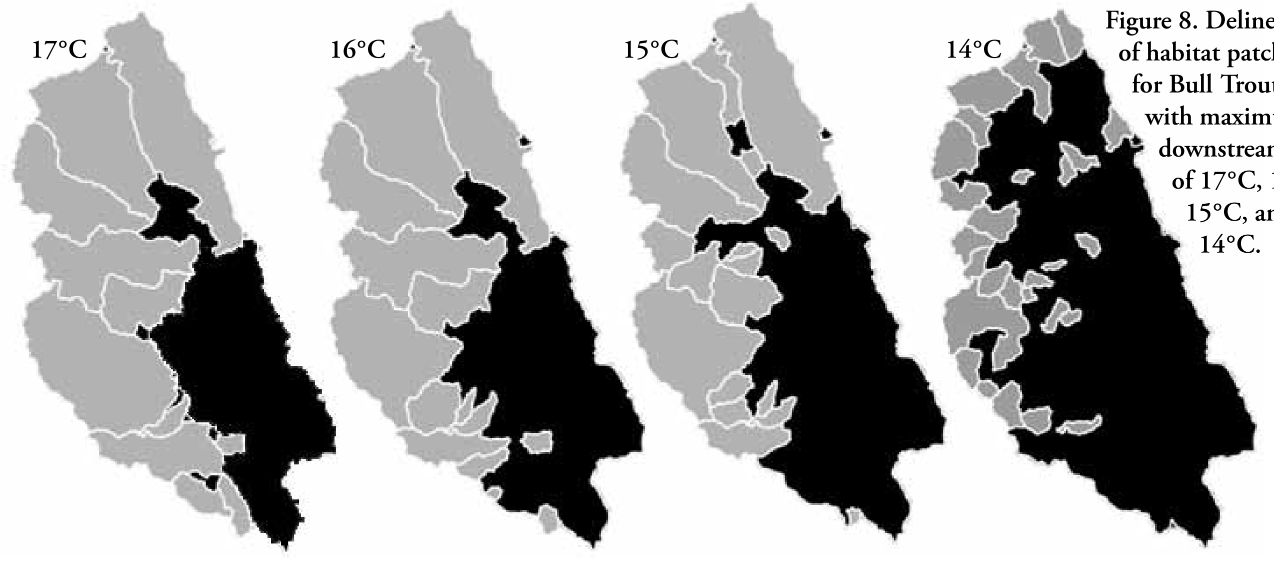


Figure 8. Delineations of habitat patches for Bull Trout with maximum downstream limit of 17°C, 16°C, 15°C, and 14°C.

Bull Trout habitat suitability modeling was performed using a Bayesian network approach (Netica software version 4.16). These models are spatially continuous throughout the Wenatchee River watershed and were performed at the spatial scale of the stream reach including the RCA for upslope inputs. Four metrics were included in determining habitat suitability: gradient (Dunham and Rieman 1999; Rich et al. 2003), scour likelihood or the number of days with flow > 95 PCTL (Wenger et al. 2011a, b), maximum annual water temperature (Dunham et al. 2002; Wenger et al. 2011 a, b) and stream width (Dunham and Rieman 1999). Maps of predicted habitat suitability were compared with known Bull Trout population locations for an assessment of model accuracy. The assessment indicated that areas identified by the models as highly suitable coincided with locations of high Bull Trout population density. Areas of highly suitable habitat were generally located in higher elevation locations that consistently contained cool water (Figure 9).

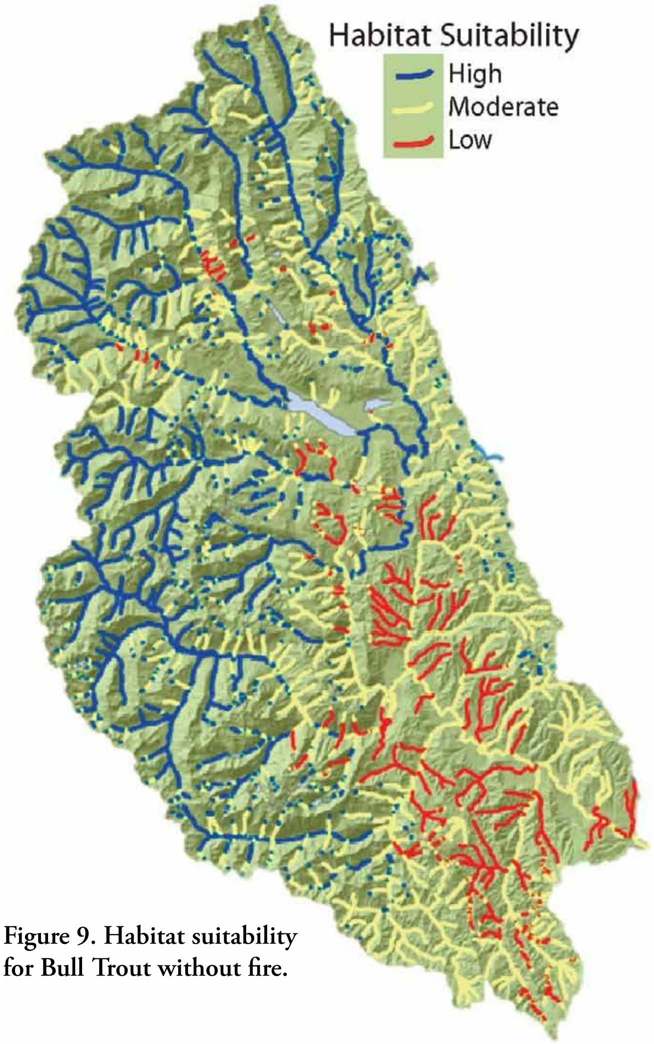


Figure 9. Habitat suitability for Bull Trout without fire.

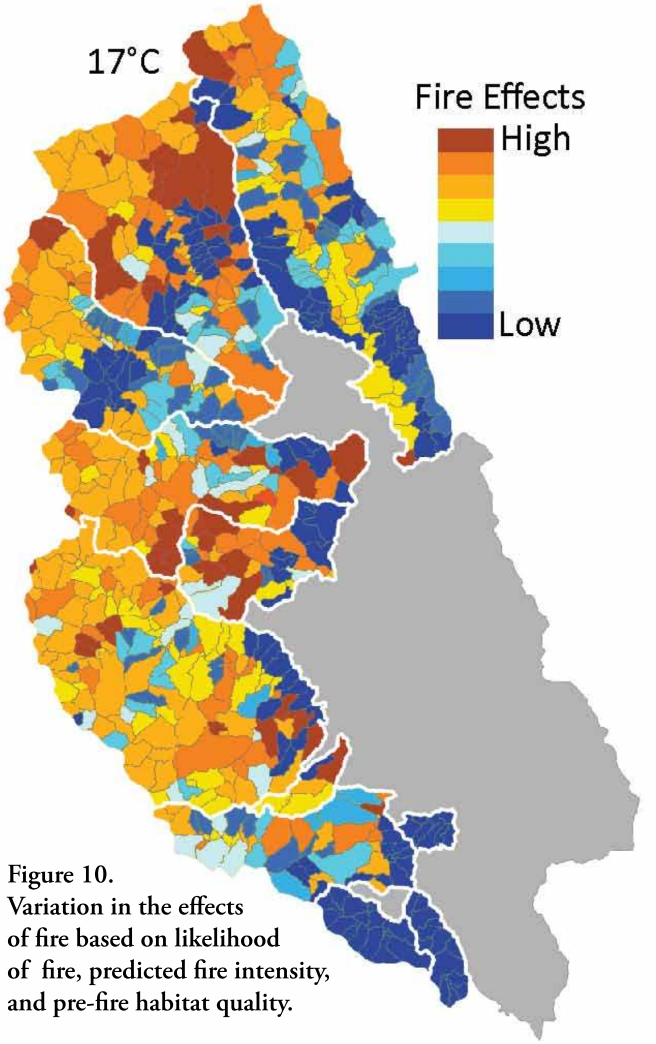


Figure 10. Variation in the effects of fire based on likelihood of fire, predicted fire intensity, and pre-fire habitat quality.

Post-fire habitat suitability was determined by modifying mean annual stream temperature to reflect the most probable fire intensity for a given stream reach (based on FlamMap predictions). Areas where fire is likely and is predicted to be severe that coincide with high quality pre-fire habitat are considered to be areas that have a higher potential to be affected by fire in ways that matter to Bull Trout (Figure 10).

The proximity of internal and external recolonization of habitat patches by surviving individuals in the event of a fire is an important element of population resilience. We determined the external and internal recolonization potential of each patch in order to determine the vulnerability of a sub-population to the effect of fire.

External recolonization represented the potential ability of individuals from different habitat patches to recolonize a patch of habitat following wildfire. This metric was calculated at the reach scale. The network distance between every reach and the nearest high-quality reach outside the originating patch was measured. This distance, the number of road crossing passed between patches, and whether the starting patch is located above an impassible barrier were all included in the calculation of recolonization potential. The location of an impassible barrier carried the most weight in determining recolonization potential because should a patch be above an impassible barrier, there is no chance of natural external recolonization (Figure 11). Natural barriers such as waterfalls and documented barriers such as the Leavenworth National Fish Hatchery on Icicle Creek were included in our analysis. Impassible culverts identified by the Washington Department of Fish and Wildlife (compiled as part of the 2004 USFWS Bull Trout Status Reassessment) were also included (StreamNet 2012). Although our selection of barriers was conservative and did not include seasonal barriers or an extensive inventory of barrier culverts, there were enough barriers in the Wenatchee River watershed to minimize the effectiveness of external recolonization as a mechanism for sub-population resilience in many patches (Figure 12).

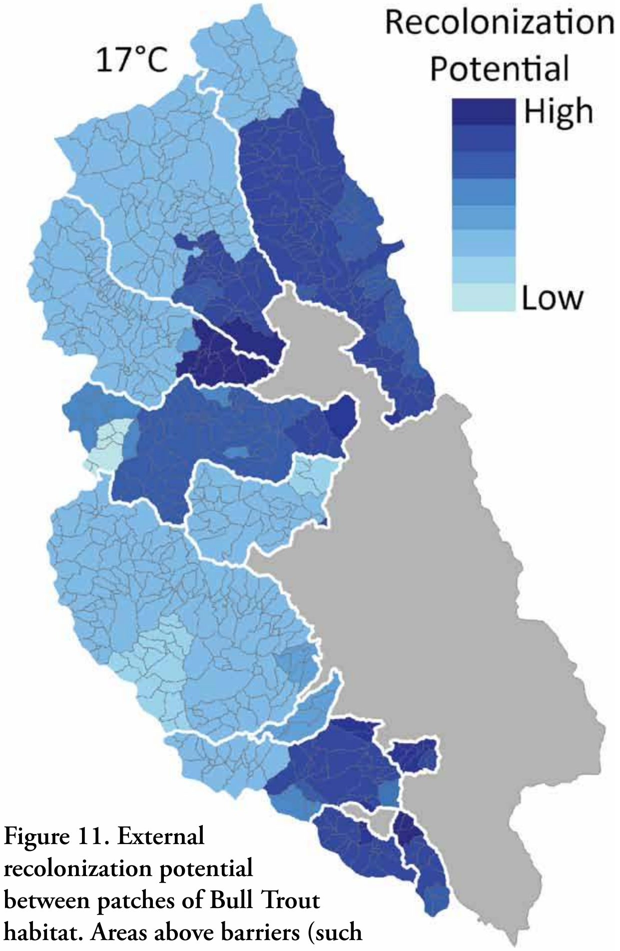


Figure 11. External recolonization potential between patches of Bull Trout habitat. Areas above barriers (such as Icicle Creek) have no natural external recolonization potential.

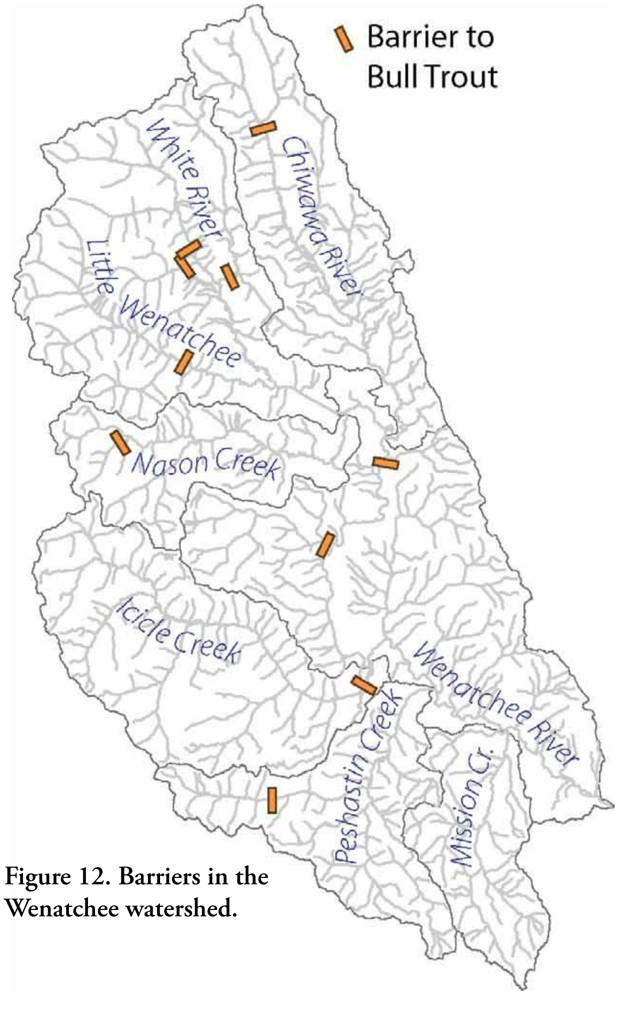


Figure 12. Barriers in the Wenatchee watershed.

Internal recolonization was calculated at the scale of a patch. The number of stream kilometers of high-quality habitat within a patch was calculated to determine the resistance of a patch to extirpation. Larger patches tended to have higher internal resistance to fire due to the availability of more high-quality habitat. Larger patches associated with 17°C, 16°C, and 15°C scenarios contained more km of high-quality Bull Trout habitat than the 14°C scenario. We also found that under the 14°C scenario, the smaller patch sizes begin to reflect the mean fire size in the Wenatchee River watershed (Figure 13). Patch sizes that are similar in size to the extent of a fire may be unable to provide any refuge habitat to fishes resident in those patches.

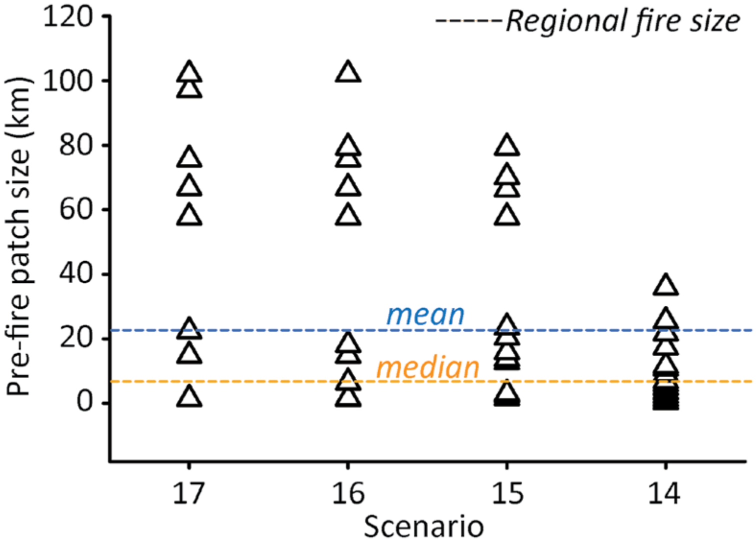


Figure 13. The length of pre-fire high-quality Bull Trout habitat in each patch at each of the four temperature-based habitat patch scenarios. At 14°C, the amount of high-quality pre-fire habitat begins to align with the mean and median regional fire size in the Wenatchee River watershed. This implies that fire may extirpate entire sub-populations of Bull Trout when their habitat patch sizes are small.

Our final model predicted the vulnerability of sub-populations of Bull Trout under each of the four scenarios that defined patch sizes of Bull Trout habitat. The final vulnerability model was completed at the reach scale, and combined potential local fire effects on habitat suitability with the potential for external and internal recolonization (Figure 14). We found that population resilience was most related to the size of existing, contiguous habitat, and the proximity of potential recolonizing individuals. Barriers to internal and external movement strongly influenced these characteristics in every scenario. Internal recolonization of patches with connected high-quality habitat that were isolated from the possibility of external colonization due to barriers was most likely when patch sizes were large. This occurred in the 17°C scenario. For example,

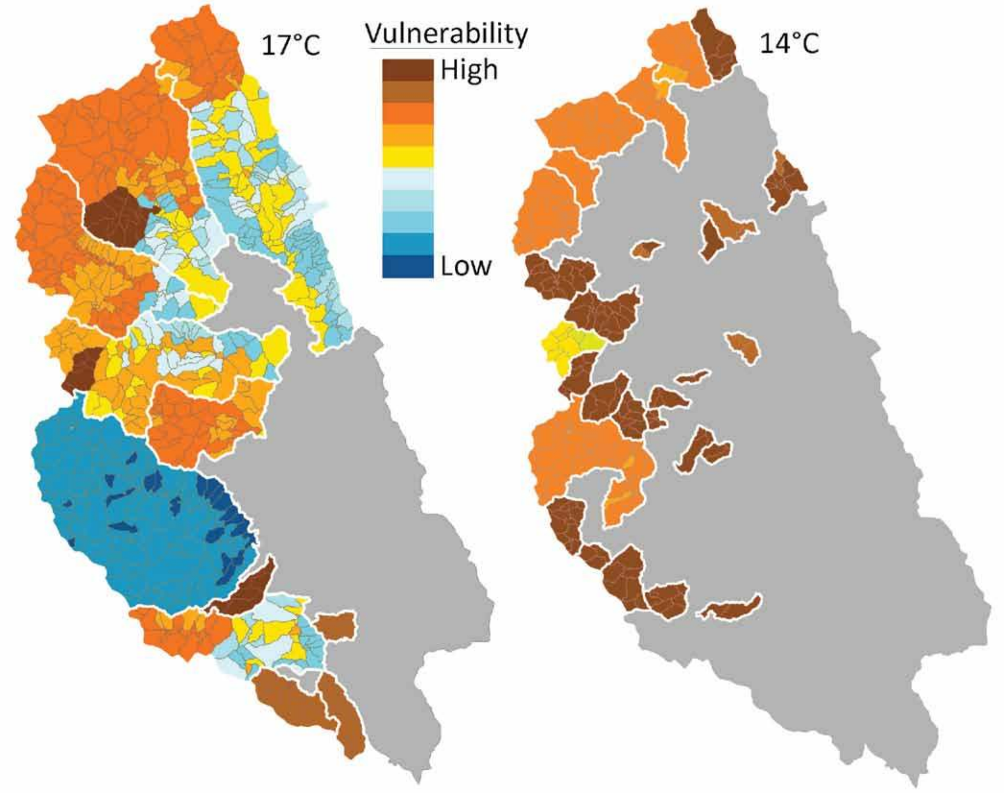


Figure 14. Vulnerability of patches containing subpopulations of Bull Trout to the effect of fire in the Wenatchee River watershed.

the weir at the Leavenworth National Fish Hatchery isolates Icicle Creek from external recolonization. However, internal connectivity within Icicle Creek under the 17°C is good, with large amounts of connected high-quality habitat. Resident populations of Bull Trout in Icicle Creek are, therefore, buffered from extirpation due to fire by internal recolonization. However, resilience based on internal recolonization weakens as the temperature-based patch scenarios constrict habitat to the upstream portions of the watershed. At the 14°C scenario, even Icicle Creek does not provide enough internal patch habitats for populations of Bull Trout to be resilient.

In smaller patches with lower internal recolonization potential, external recolonization potential becomes more important in determining population resilience for Bull Trout. This is the case for patches of Bull Trout located in the Chiwawa and Little Wenatchee Rivers. While each of these watersheds under the 17°C scenario also offers strong internal recolonization potential, under the other temperature scenarios, external recolonization becomes important. These two watersheds drain into Lake Wenatchee. This large freshwater feature facilitates spatially close connections among incoming tributaries, thereby strengthening the role recolonization plays in determining resilience of fish populations under all temperature scenarios.

Application—The potential effect of large-scale disturbance such as fire on the population vulnerability of fish populations is an important consideration when determining management actions in a watershed. We modeled the resilience of Bull Trout populations based on the extent and location of habitat features throughout the Wenatchee River watershed. We did this by assessing the connectivity among habitat within and between patches, combined with the quality of habitat pre- and post-fire. Our results indicated the importance of preserving and enhancing stream network connectivity at reach and watershed scales. For example, in some patches, such as Icicle Creek, population resilience is grounded in the internal connectedness of high-quality habitat. In Icicle Creek, external recolonization does not contribute to population resilience due to the barrier of the Leavenworth National Fish Hatchery. Because of the absence of external recolonization in this watershed, management must be careful to protect available internally connected habitats within the stream network. Other areas, such as the subwatersheds draining into Lake Wenatchee, have high-quality habitat within habitat patches, and populations are made more resilient due to the close proximity of other habitat patches. The location and connectivity among watersheds provided by Lake Wenatchee is important for resilience of local Bull Trout populations. Due to the size of habitat patches in this area under every temperature scenario that we modeled, the watersheds that drain into Lake Wenatchee may represent an area that could function as a population stronghold for the entire Wenatchee River watershed. Management that ensures fish access into and out of Lake Wenatchee may be important for maintaining Bull Trout populations throughout the Wenatchee River watershed.

Spring Chinook Salmon

Historically, populations of wild spring-run Chinook Salmon were distributed throughout the mainstem of the Wenatchee River and its major tributaries (Honea et al. 2009). Returning adults are highly mobile and have the potential to colonize new habitats. Currently these fish are considered endangered in the Wenatchee River watershed. Unlike Bull Trout, which may have isolated resident populations above barriers, spring Chinook occupy only sections of river that are ultimately connected to the ocean on their downstream end. Due to barriers and habitat quality, the current distribution of spring Chinook is presently limited to portions of the Chiwawa, White, Little Wenatchee, Nason Creek, and Icicle Creek subwatersheds (Figure 15).

These endangered fish have specific habitat requirements that can be quantified for each life-history stage. The objective of our modeling work was to map habitat quality for each life-history stage of spring Chinook throughout the Wenatchee River watershed, in order to use fire model output to predict changes in habitat for spring Chinook post-fire. Rather than modeling only the truncated current distribution of spring

Chinook, we modeled the potential effect of fire on aquatic habitat for all stream reaches in the historic distribution of the species (Figure 15). By modeling the availability and configuration of habitat, we assessed the vulnerability to fire of spring Chinook in major subwatersheds of the Wenatchee River system.

The availability, quality, and connectivity of habitats necessary for each life-history stage of spring Chinook was assessed for pre- and post-fire in-stream habitat conditions. Empirical data and published literature established habitat needs for each life-history stage (egg, juvenile, and spawning adult) (Honea et al. 2009; Jorgensen et al. 2009). Two spatial extents were used for this analysis: 200-meter stream reaches and subwatersheds.

Habitat needs of spawning spring Chinook were integrated into a Bayesian belief network model (Netica software version 4.16) (Figure 16). The geomorphic suitability of stream reaches was characterized based on channel type and substrate. Water temperature during the time of peak spawning (August through September) and wood recruitment were also modeled for each reach. These reach characteristics were combined to characterize a reach as high, moderate, or poor quality for spawning spring Chinook under pre- or post-fire conditions. Results were then mapped using geographic information system software (ESRI ArcGIS version 9.3) (Figure 17).

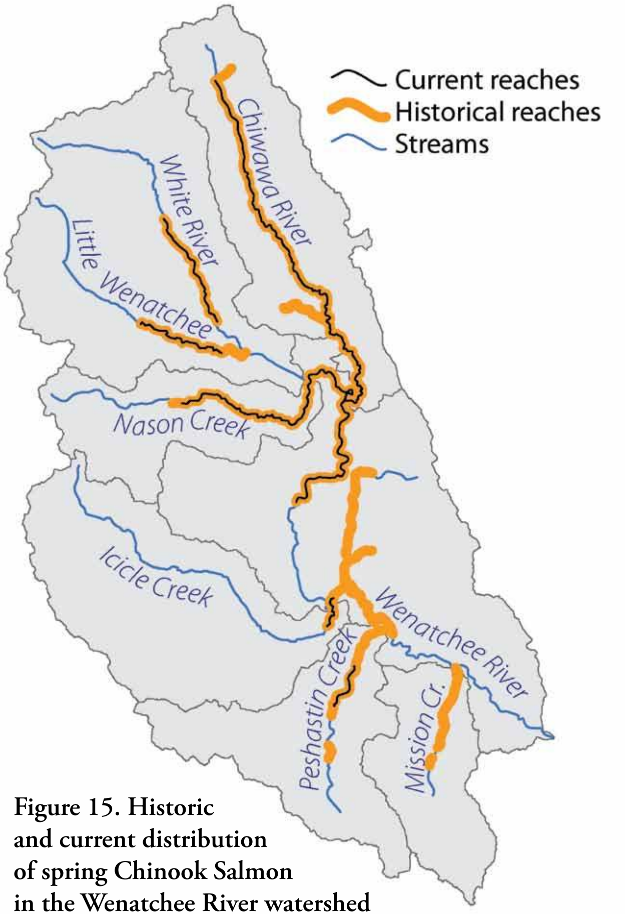
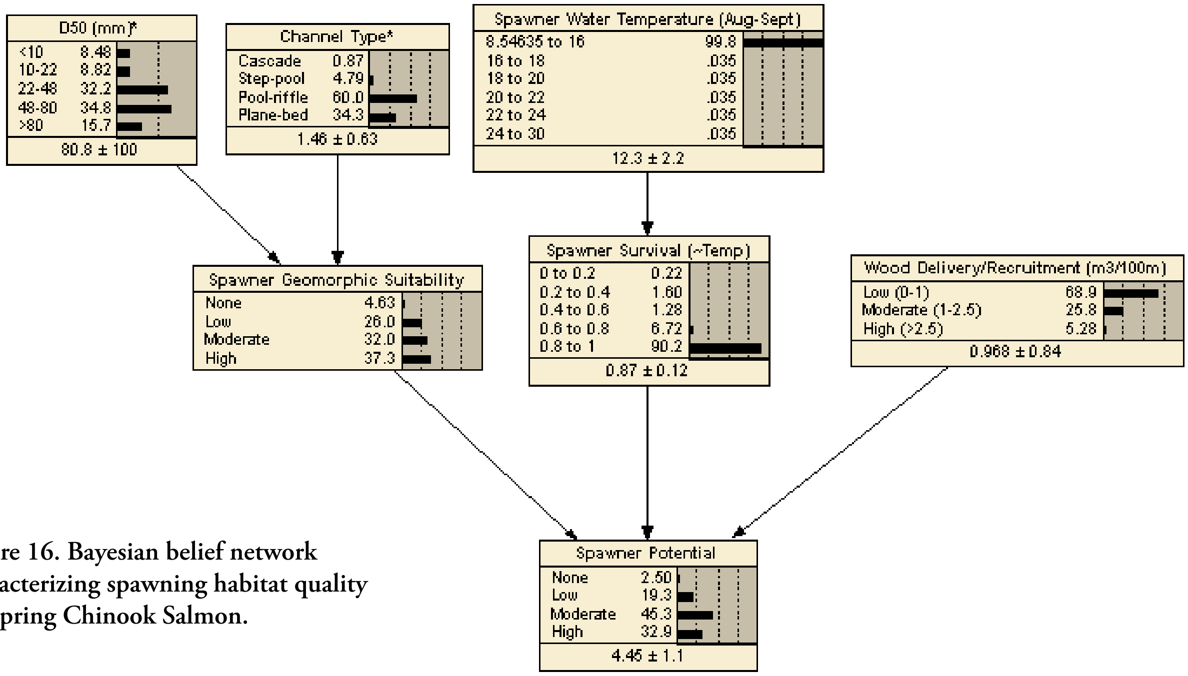


Figure 15. Historic and current distribution of spring Chinook Salmon in the Wenatchee River watershed (Honea et al. 2009).



D50 (mm)*	
<10	8.48
10-22	8.82
22-48	32.2
48-80	34.8
>80	15.7
80.8 ± 100	

Channel Type*	
Cascade	0.87
Step-pool	4.79
Pool-riffle	60.0
Plane-bed	34.3
1.46 ± 0.63	

Spawner Water Temperature (Aug-Sept)	
8.54635 to 16	99.8
16 to 18	.035
18 to 20	.035
20 to 22	.035
22 to 24	.035
24 to 30	.035
12.3 ± 2.2	

Spawner Geomorphic Suitability	
None	4.63
Low	26.0
Moderate	32.0
High	37.3

Spawner Survival (~Temp)	
0 to 0.2	0.22
0.2 to 0.4	1.60
0.4 to 0.6	1.28
0.6 to 0.8	6.72
0.8 to 1	90.2
0.87 ± 0.12	

Wood Delivery/Recruitment (m3/100m)	
Low (0-1)	68.9
Moderate (1-2.5)	25.8
High (>2.5)	5.28
0.968 ± 0.84	

Spawner Potential	
None	2.50
Low	19.3
Moderate	45.3
High	32.9
4.45 ± 1.1	

Figure 16. Bayesian belief network characterizing spawning habitat quality for spring Chinook Salmon.

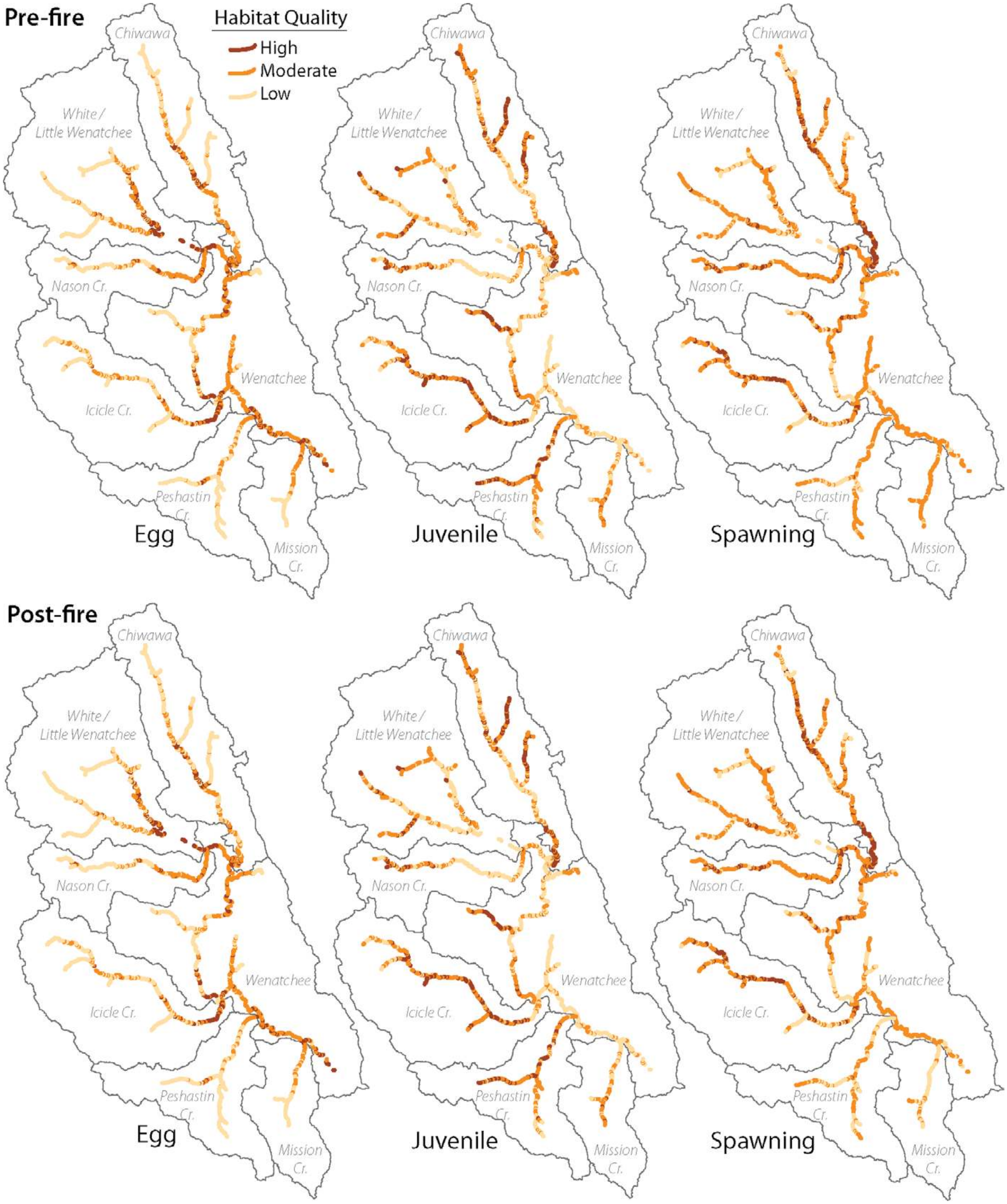


Figure 17. Pre- and post-fire distributions of habitat quality for the egg, juvenile, and adult life-stages of spring Chinook Salmon.

We found no change in the number of reaches identified as high-quality spawning habitat for spring Chinook post-fire. This indicates that high-quality spawning locations may currently be located in areas of predicted low-fire intensity. However, 8% of reaches that had been identified as moderate quality were reduced to low quality post-fire (Table 2).

Table 2. Summary of Chinook Salmon habitat quality classification of 200-m reaches pre- and post-fire using the most probable fire intensity (as identified by FlamMap modeling).

Life-stage	Fire Intensity	Total Reaches		% Change
		Pre-fire	Post-fire	
Egg	Low	955	1057	5
	Moderate	818	732	-4
	High	257	241	-1
Juvenile	Low	890	890	0
	Moderate	832	832	0
	High	308	308	0
Adult	Low	401	554	8
	Moderate	1363	1208	-8
	High	266	266	0

Habitat conditions for spring Chinook eggs and juveniles were modeled separately using Bayesian belief network models. Models for egg survival were based on water temperature (pre- and post-fire) during incubation (August through May) and predicted quantities of fine sediments (pre- and post-fire). Juvenile overwinter models combined the geomorphic suitability of the stream reach (characterized by sediment and channel type) and wood recruitment. Characterization of a reach as high, moderate, or poor quality for each of these life-history stages under pre- or post-fire conditions was determined and mapped using geographic information system software (ESRI ArcGIS version 9.3) (Figure 17). We found no changes in habitat quality for the juvenile life-history stage post-fire but did see a drop in high-quality and moderate-quality egg habitat, with a coincident increase in low-quality egg habitat post-fire (Table 2). We suspect that our models are not currently sensitive enough to detect changes in habitat quality for the juvenile life-stage. Additional analysis that refines model sensitivity by including additional variables that describe local habitat conditions will need to be conducted.

Habitat quality for each of the three life-history stages was combined into an overall habitat quality metric for pre- or post-fire condition. We assigned values of 1 for low-quality, 2 for moderate-quality and 3 for high-quality habitat for each life-history stage, and then calculated the geometric mean for every reach (Figure 18).

To explore population vulnerability of spring Chinook, we subdivided the Wenatchee River watershed into seven subwatersheds (Chiwawa, Icicle, Mission, Nason, Peshastin, Wenatchee, White/ Little Wenatchee). We wanted to explore which subbasins contained high-quality habitat for all life stages of Chinook Salmon under pre- and post-fire conditions. Based on the geometric mean for habitat quality, averaged for each subwatershed, we found that all watersheds experienced a reduction in habitat quality post-fire. Mission Creek appeared to have the largest potential decrease in overall habitat quality based on the subwatershed-scale geometric mean (Table 3). When we looked closer at the percent of available high-quality habitat for each life stage within each subwatershed, Mission Creek also appeared to be the watershed with the smallest amount of high-quality habitat for the juvenile and adult life-history stages in either pre- or post-fire conditions (Table 4). Historically, the Mission Creek subwatershed contained spring Chinook, but it is not part of the current distribution of the species. Peshastin and Mission Creeks appear to have limited amounts of high-quality egg-stage habitat and adult spawning habitat. A small and isolated portion of Peshastin Creek currently supports spring Chinook. Sedimentation in areas with isolated populations or poor egg habitat conditions may fare poorly under high-intensity fire (Burton 2005). This makes the Peshastin Creek subwatershed an area of potential concern. The Chiwawa and Icicle Creek watersheds appear to contain the largest quantity of high-quality habitat for all life stages (Table 4). However, the migration barrier located at the Leavenworth National Fish Hatchery blocks access by spring Chinook to potential habitats in the Icicle Creek subwatershed.

The effect of fire on spring Chinook Salmon habitat is relatively minor. A small decrease in habitat quality is currently predicted based on the most probable fire intensity (from FlamMap, Finney 2006). However, much of the area occupied by spring Chinook in the Wenatchee River watershed is found in areas where the most probable fire intensity is "low" or "moderate" but not "high". Because we saw a decrease in habitat quality with low and moderate fire intensity, we should expect a larger decrease in habitat quality should high- intensity fire occur within the distribution of spring Chinook. The assessment of life-history stage habitat quality indicates that several subwatersheds in the Wenatchee River watershed lack high-quality habitat for each life-history stage. This indicates that stream restoration efforts may be more effective if they consider the strengths and weaknesses of available habitat at each life stage.

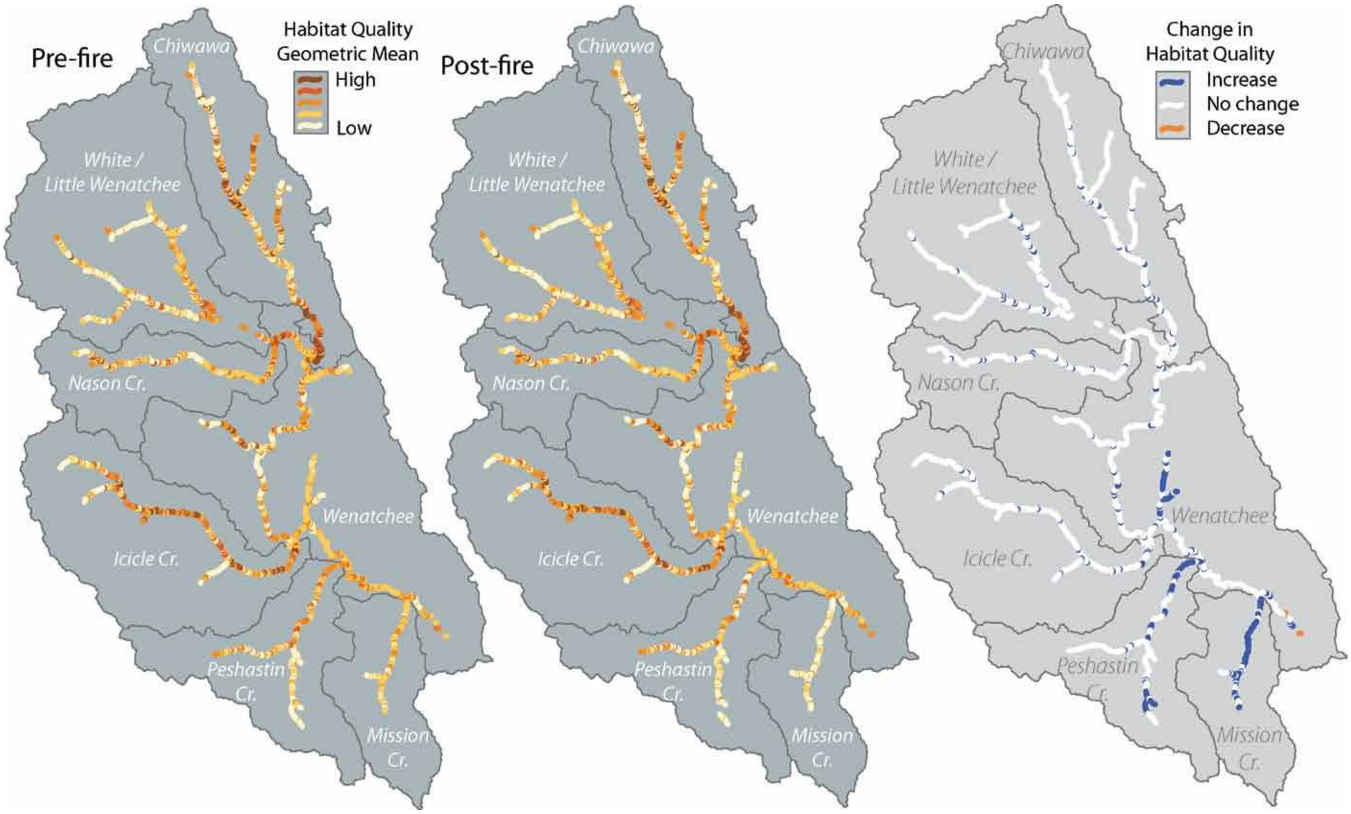


Figure 18. Pre- and post-fire habitat quality for Chinook Salmon, summarized using the geometric mean of habitat quality designations for each life-history stage.

Table 3. Differences in the geometric mean of low-, moderate-, and high-quality habitat conditions summarized at the reach scale for seven subwatersheds identified within the Wenatchee River watershed. Habitat condition values: 1 = low-quality, 2 = moderate-quality, 3 = high-quality.

		Geometric Mean of Habitat Conditions		
Subwatershed	n	Pre-fire	Post-fire	Pre- to Post-fire Change
Chiwawa	393	2.13	2.12	0.005
Icicle	285	2.14	2.13	0.005
Mission	93	2.06	1.99	0.074
Nason	188	2.09	2.09	0.006
Peshastin	194	2.07	2.04	0.029
Wenatchee	508	2.09	2.08	0.012
White/Little Wenatchee	369	2.06	2.06	0.005

Table 4. The estimated percent of available habitat within each subwatershed of the Wenatchee River watershed classified as high quality for each life-history stage in pre- and post-fire conditions.

	Percent of Total Available Habitat					
	Egg		Juvenile		Adult	
Subwatershed	Pre-fire	Post-fire	Pre-fire	Post-fire	Pre-fire	Post-fire
Chiwawa	9	9	27	27	30	30
Icicle	12	12	28	28	26	26
Mission	4	3	3	3	0	0
Nason	7	6	9	9	17	17
Peshastin	3	2	22	22	1	1
Wenatchee	19	18	7	7	5	5
White/Little Wenatchee	17	17	7	7	5	5

Application—The potential of fire to enhance or degrade habitats for endangered salmonids is an important concern for forest managers. We modeled the resilience of spring Chinook populations to fire in the Wenatchee River watershed by assessing habitat needs for each life stage of the fish in the system. We found that detrimental effects of fire on high-quality Chinook habitat are minor. This is most likely due to the predicted fire intensity in these areas (which are “low” or “moderate”). Further, at the subwatershed-scale, we found that high-quality habitat for each life stage is not always present. In natural river systems that are driven by spatially and temporally diverse disturbance events, historic habitat quality would have reflected a mix of conditions (Reeves et al. 1995). However, few subwatersheds in the Wenatchee River system currently contain large amounts of high-quality habitat. Our analysis identifies the quantity of available high-quality habitat for spring Chinook at each life stage in each subwatershed. This offers managers the opportunity to target enhancement at a subwatershed-scale. For example, subwatersheds with already minimal quantities of high-quality egg and juvenile habitat may need to be protected from increased sedimentation that could result from fire. It is also possible that some locations may respond well to fire. While fine sediment associated with fire has negative short-term consequences on habitat quality for some life stages, other life stages will benefit from the addition of larger sediment and wood to the stream channel to enhance habitat complexity over the long-term. For example, locations in need of complex habitat to develop spawning gravels may be good locations to allow fire to occur.

Relationship to Other Recent Findings and Ongoing Work on this Topic

This project relied heavily on the current generation of FlamMap predictions developed by Paul Hessburg. The innovations that Paul has made to FlamMap allowed for greater confidence in predicted fire severity for the Wenatchee River watershed. The spatial tools that predict sediment, wood delivery, and temperature were each modeled for low-, moderate-, and high-severity conditions. This will allow us to essentially “game” the watershed using different levels of fire intensity. Those different levels of fire intensity may be the result of more advanced fire predictions using models such as FlamMap, or as a result of changes in management that may alter predicted fire intensity.

Earth Systems Institute participated in this project by developing the geospatial tools to model sediment delivery and wood recruitment as a result of fire intensity. ESI is continuing work predicting the potential effect of fire on aquatic habitat by participating in a project through the Western Wildlands Environmental Threat Assessment Center that couples the NetMap fire hillslope erosion and road risk assessment tools with fire-risk predictions. This project is designed to be part of the process that Burned Area Response Teams can use to assess the effect of fire on aquatic habitats. This work is being conducted across northern California, encompassing eight national forests.

The Bull Trout population vulnerability work has the potential to be integrated into a regional effort led by Jason Dunham to assess the population viability of Bull Trout in the face of climate change in the interior western states.

Future Work

Additional work modeling spring Chinook Salmon population vulnerability in the Wenatchee River watershed is needed. Considering the potential differences in distribution and habitat use among wild and hatchery fish in response to fire would be valuable, considering the strong influence of hatchery fish and their potential role in population resilience for this watershed (Honea et al. 2009).

Additional research on fire prescriptions in forest landscapes that links ecosystem and geomorphic/hydrologic processes is also needed (Rieman and Clayton 1997; Rieman et al. 2010) to assist forest managers as they implement aspects of recovery plans for imperiled aquatic species. An evaluation of specific management approaches is needed that considers the diverse survival strategies of native species, within the context of predicted ecosystem processes. Increased knowledge about this approach may help forest managers better balance the needs of the natural community with human land use. Useful techniques and tools would couple fuel-loading conditions for forest management and landscape-scale restoration of physical and biological processes that underlie functional aquatic and terrestrial ecosystems.

Combining the metapopulation perspective for aquatics with terrestrial species of interest, particularly , Northern Spotted Owls and Barred Owls (Strix occidentalis caurina and Strix varia) may be a very useful tool for future planning of riparian management strategies. Barred Owls were first detected in the Wenatchee River watershed in the early 1980s, and are now relatively common in the area (Singleton et al. 2010). Riparian management for fish habitat values may in some cases conflict, and may need to be balanced against, landscape management that encourages Spotted Owls and discourages Barred Owls.

Deliverables

In our project proposal, we identified peer-reviewed publications, presentations at professional meetings, and a training session as project deliverables.

There are currently three publications being prepared for submission to peer-reviewed journals. These include:

- *Life-history habitat needs of spring Chinook in a pre- and post-wildfire landscape*, for consideration by Transactions of the American Fisheries Society
- *Fish and fire: Vulnerability analysis for Bull Trout across a wildfire-prone landscape*, for consideration by the Canadian Journal of Fisheries and Aquatic Sciences
- *Predicting pre- and post-fire stream temperature in the Wenatchee River basin, Washington*, for consideration by the journal Ecological Applications.

Presentations have been made to forest fire managers and biologists and at a professional meeting.

- We organized a one-day workshop titled “Compatibilities of Managing for Fish and Fire Simultaneously” at the Wenatchee-Okanagan National Forest Headquarters in Wenatchee, Washington (May 2011) to seek input from forest managers, hydrologists, fish biologists, and terrestrial ecologists regarding the modeling framework, approach, and utility of the applications being developed.
- We organized a session titled “The Effect of Fire on Native Fishes in the West” that was presented at the Oregon Chapter of the American Fisheries Society (February 2012).

Additionally, most of the geographic information system applications that we developed to model the effect of fire on sediment and wood recruitment are currently available online (www.netmaptools.org). A webinar covering the use of these newly developed geospatial tools was also completed (2012).

References

Agar, A.A., M.A. Finney, B.K. Kerns, and H. Maffei. 2007. Modeling wildfire risk to northern spotted owl (*Strix occidentalis caurina*) habitat in Central Oregon, USA. *Forest Ecology and Management* 246: 45-56.

Benda, L.E., C. Veldhuisen, and J. Black. 2003. Debris flows as agents of morphological heterogeneity at low-order confluences, Olympic Mountains, Washington. *Geological Society of America Bulletin* 115: 1110-1121.

Benda, L., D. Miller, K. Andras, P. Bigelow, G. Reeves, and D. Michael. 2007. NetMap: A new tool in support of watershed science and resource management. *Forest Science* 53(2): 206-219.

Bigelow, P.E., L.E. Benda, D.J. Miller, and K.M. Burnett. 2007. On debris flows, river networks, and the spatial structure of channel morphology. *Forest Science* 53: 220-238.

Bisson, P.A., and G.E. Davis. 1976. Production of juvenile Chinook salmon, *Oncorhynchus tshawytscha*, in a heated model stream. *NOAA Fisheries Bulletin* 74(4):763-774.

Bisson, P.A., Rieman, B.E., Luce, C., Hessburg, P.F., Lee, D.C, Kershner, J.L., Reeves, G.H., Gresswell, R.E. 2003. Fire and aquatic ecosystems of the western USA: current knowledge and key questions. *Forest Ecology and Management* 178: 213-229.

Burton, T. 2005. Fish and stream habitat risks from uncharacteristic wildfire: observations from 17 years of fire-related disturbances on the Boise National Forest, Idaho. *Forest Ecology and Management* 211: 140-149.

Dunham, J.B, and B.E. Rieman. 1999. Metapopulation structure of bull trout: influences of physical, biotic, and geometrical landscape characteristics. *Ecological Applications* 9(2): 642-655.

Dunham, J.B., B.S. Cade, and J.W. Terrell. 2002. Influences of spatial and temporal variation on fish-habitat relationships defined by regression quantiles. *Transactions of the American Fisheries Society* 131(1): 86-98.

Dunham, J.B., M.K. Young, R.E. Gresswell, B.E. Rieman. 2003. Effects of fire on fish populations: landscape perspectives on persistence of native fishes and nonnative fish invasions. *Forest Ecology and Management* 178; 183-196.

Dunham, J.B., A.E. Rosenberger, C.H. Luce, and B.E. Rieman. 2007. Influences of wildfire and channel reorganization on spatial and temporal variation in stream temperature and the distribution of fish and amphibians. *Ecosystems* 10: 335-346.

Finney, M.A. 2006. An overview of FlamMap fire modeling capabilities. Pages 127-124 in Andrews, P.L., and B.W. Butler, comps. 2006. *Fuels Management-How to Measure Success: Conference Proceedings*. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Gresswell, R.E. 1999. Fire and aquatic ecosystems in forested biomes of North America. *Transactions of the American Fisheries Society* 128: 193-221.

Groom, M.J., and N. Schumaker. 1993. Evaluating landscape change: patterns of worldwide deforestation and local fragmentation. Pages 24-44 in Kareiva, P.M., J.G. Kingsolver, and R.B. Huey (eds.), *Biotic Interactions and Global Change*. Sinauer Assocuates Inc., Sunderland, MA.

Honea, J.M., J.C. Jorgensen, M.M. McClure, T.D. Cooney, K. Engie, D.M. Holzer, and R. Hilborn. 2009. Evaluating habitat effects on population status: influence of habitat restoration on spring-run Chinook salmon. *Freshwater Biology* 54: 1576-1592.

Jorgensen, J.C., J.M. Honea, M.M. McClure, T.D. Cooney, K. Engie, and D.M. Holzer. 2009. Linking landscape-level change to habitat quality: an evaluation of restoration actions on the freshwater habitat of spring-run Chinook salmon. *Freshwater Biology* 54:1560-1575.

Kennedy, P.L., and J.B. Fontaine. 2009. Synthesis of knowledge on the effects of fire and fire surrogates on wildlife in U.S. dry forests. Special Report 1096. Oregon State University Agricultural Experiment Station, Corvallis, Oregon, USA.

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. EPA 910-R-99-010. Seattle, Washington, USA: U.S. Environmental Protection Agency, Region 10. Available at: http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1004JG1.txt

Miller, D.J., and K.M. Burnett. 2007. Effects of forest cover, topography, and sampling extent on the measured density of shallow, translational landslides. *Water Resources Research* 43:W03433.

Neuheimer, A.B., and C.T. Taggart. 2007The growing degree-day and fish size-at-age: the overlooked metric. *Canadian Journal of Fisheries and Aquatic Sciences* 64: 375-385.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, P.A., and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. *American Fisheries Society Symposium* 17:334-349.

Rich, D.F., T.E. McMahon, B.E. Rieman, and W.L. Thompson. 2003. Local-habitat, watershed, and biotic features associated with bull trout occurrence in Montana streams. *Transactions of the American Fisheries Society* 132:1053-1064.

Rieman, B.E., and J.L. Clayton. 1997. Wildfire and fish: issues of forest health and conservation of native fishes. *Fisheries* 22: 6-15.

Rieman, B.E., and J.B. Dunham. 2000. Metapopulations and salmonid fishes: a synthesis of life history patterns and empirical observations. *Ecology of Freshwater Fish* 9: 1-64.

Rieman, B.E., Hessburg, P.F., Luce, C., Dare, M.R. 2010. Wildfire and management of forests and native fishes: conflict or opportunity for convergent solutions? *BioScience* 60:460-468.

Salmon, Steelhead, and Bull Trout Habitat Limiting Factors. 2001. Report developed by the Technical Advisory Committee mandated by the RCW 77.85.070 (Salmon Recovery Act). Olympia, Washington, pp. 347.

Selong, J.H., T.E. McMahon, A.V. Zale, and F.T. Barrows. 2001. Effect of temperature on growth and survival of bull trout with application of an improved method for determining thermal tolerance in fishes. *Transactions of the American Fisheries Society* 130:1026-1037.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for Wenatchee, WA. Available online at http://soildatamart.nrcs.usda.gov.

Singleton, P.H., J.F. Lehmkuhl, and W.L. Gaines. 2010. Barred owl space use and habitat selection in the Eastern Cascades, Washington. *Journal of Wildlife Management* 74: 285-294.

StreamNet GIS Data. 2012. Metadata for the 2004 USFWS Bull Trout Status Reassessment: Washington Department of Fish and Wildlife: StreamNet. URL: http://www.streamnet.org/online-data/GISData.html.

Wenger, S.J, D.J. Isaak, J.B. Dunham, K.D. Fausch, C.H. Luce, H.M. Neville, B.E. Rieman, M.K. Young, D.E. Nagel, D.L. Horan, and G.L. Chandler. 2011a. Role of climate and invasive species in structuring trout distributions in the interior Columbia River Basin, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 68:988-1008.

Wenger, S.J., D.J. Isaak, D.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Wlsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams. 2011b. Flow regime, temperatures, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences USA* 108(34):14175-14180.