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Conservation Planning for Climate Change Impacts to Benthic Macroinvertebrate Assemblages in the Columbia River Basin

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Introduction

This assessment considers the vulnerability of benthic macroinvertebrate assemblages and their vulnerabilities to climate change impacts in the Columbia River Basin. We also explore potential strategies for resource managers to mitigate for these vulnerabilities. A three-step decision support framework for climate adaptation (Nelson et al. 2016) has been used to present these findings in a consistent format with other ongoing vulnerability assessments within the Columbia Basin Partner Forum (CBPF). The CBPF is an interdisciplinary group of federal, state, local, and tribal resource managers and scientists that meets periodically to address issues relating to climate change and the Columbia River Basin, with the support and guidance of the Great Northern Landscape Conservation Cooperative (2017).

This document is intended to assist resource managers and researchers in the following ways:

(1) By referencing selected literature, expertise, and data on the likely impacts of climate change on benthic macroinvertebrate assemblages;

(2) By highlighting research needs to better understand future impacts;

(3) By generating a set of management actions towards mitigating negative impacts on these assemblages, and aide their long-term integrity;

(4) By providing this information using a standard approach and format, which is being used to assess the vulnerabilities of other species and habitats in the Columbia River basin.

Conservation Target

This climate vulnerability assessment for benthic macroinvertebrates employs an assemblage-level approach, rather than the population-level approach developed for salmonids by Nelson et al. (2016). In this report, an assemblage or community refers to multiple interacting populations of organisms having substantial overlap in timing and occurrence. In general, biotic community composition is considered one of several essential biodiversity variables, relevant for indicating trends in condition and vulnerability of ecosystems to climatic impacts (Pereira et al. 2003). Climate change may have more profound effects on overall community structure (Burgmer et al. 2007) or water quality metrics calculated from taxonomic composition (Hamilton et al. 2010) than on individual species. We place special focus on taxa within the benthic macroinvertebrate assemblage having life history, ecological, and behavioral traits that make them important food resources for stream-dwelling salmonids (Rader 1997; Sullivan and White 2017), or otherwise critical components of riverine food webs (Figure 1) (ISAB 2011; Naiman et al. 2012). Our decision to take an assemblage-level approach necessarily overlooks vulnerability of individual taxa—for example native freshwater mussels (Nedeau et al. 2009) or crayfish (Larson and Olden 2011)—that may benefit from their own vulnerability assessments.

Figure 1. Aquatic insect larvae, such as this caddisfly (top), stonefly (middle), and mayfly (bottom), are excellent indicators of stream health and are important components of food webs in aquatic ecosystems. Photo copyright: Guenter A. Schuster https://www.flickr.com/photos/ksnpc/6289538084

Geographic Scope

This assessment is focused on the streams and rivers of the Columbia River Basin that provide habitat to salmonids, including anadromous salmon, steelhead, and resident trout. Freshwater lotic ecosystems (flowing rivers and streams) are the principal habitat type for a wide range of benthic macroinvertebrates that are food sources for these fish, including species of mayflies (order Ephemeroptera), stoneflies (order Plecoptera), caddisflies (order Trichoptera), and others. Figure 2 shows the major watersheds of this region, which provide habitat for benthic macroinvertebrate assemblages.

Figure 2. Major rivers of the Columbia River basin.

Increasing air temperatures predicted for the 21st century are expected to reduce seasonal snowpack as more precipitation falls as rain and less as snow (Mote et al. 2014). This is expected to alter the timing of stream flow, with increases to seasonal and peak flows occurring between December and April, and lower stream flows between June and September (ISAB 2007). The extent of these changes is expected to be greatest in mid-elevation "transient" watersheds with moderate winter air temperatures, where precipitation will change from snow to rain (Mantua et al. 2010; Hamlet et al. 2013). Higher air temperatures and reduced stream flows are expected to increase water temperatures in regional streams (ISAB 2007; Isaak et al. 2012). Summer water temperatures in streams with larger relative groundwater inflows are expected to warm less than streams with lower groundwater contributions (ISAB 2007; Isaak et al. 2012). Climate change is expected to reduce cold-water fish habitat in Columbia River Basin tributaries, with the greatest effects to occur in streams of mid-elevation watersheds, areas east of the Cascade crest, southern portions of the basin, and in areas without permeable geology (ISAB 2007).

Step 1: Assess Vulnerability

The vulnerability assessment was performed under a three-step process recommended by the CBPF of the Great Northern Landscape Conservation Cooperative. Under step 1 of this process, the vulnerability of benthic macroinvertebrate assemblages of the Columbia River Basin to climate change impacts was assessed. This was achieved through a review of key literature and regional professional expertise on the status and ecological characteristics of macroinvertebrates, and the likely climate change impacts to benthic macroinvertebrate assemblages. The findings are delineated into sections on habitat suitability, biotic interactions, and habitat connectivity. These findings are summarized in a vulnerability matrix (Table 1).

Habitat Suitability

In general, invertebrates worldwide (terrestrial, marine, and freshwater) are highly susceptible to climate change impacts (Prather et al. 2009). Previous research has demonstrated several characteristics that can make invertebrates vulnerable to climate change, including narrow thermal tolerances, narrow moisture tolerances, synergistic effects to multiple stressors, low fecundity, low abundance, restricted range, long recovery time after disturbances, climate-related breeding requirements, low within-population genetic variation, specialist behavior, mutualist behavior (dependent on other species), and temporal mismatches with other species (Prather et al. 2009). A study of caddisflies (Trichoptera) across 23 European ecoregions revealed several traits making certain species more vulnerable to climate change: endemism, preference for springs, preference for cold water temperatures, short emergence period, and restricted ecological niches in terms of feeding types (Hering et al. 200). Because of their strict physiological tolerances, caddisflies, stoneflies, and mayflies may be among the most vulnerable to climate-induced changes in water temperature (Li et al. 2013).
Haidekker and Hering (2008) found that benthic insect assemblages in mountainous areas of central Europe become less specialized with warming river temperatures, and that those in small streams are affected more than those in large streams. Durance and

Ormerod (2007) examined data in a UK headwaters streams to test relationships between macroinvertebrate abundance and climatic variables. They found that abundance declines with increasing temperatures, and that less common species are most affected. However, an assessment of changes in abundance of individual stream macroinvertebrates in North Carolina and the Mid-Atlantic Highlands of the U.S. revealed that historically common taxa can also be highly vulnerable to biological, physical, and chemical water quality (Hawkins and Yuan 2016). A study in New South Wales demonstrated that families of stream macroinvertebrates that favor cold water and higher streamflow were most vulnerable to conditions expected under climate change (Chessman 2009). Thermal preference of benthic macroinvertebrates showed promise towards climate sensitivity using a long-term dataset from Maine, North Carolina, and Utah. Across the entirety of the U.S., stream temperature is a primary determinant of the macro-spatial distribution of benthic macroinvertebrate assemblages (Hill and Hawkins 2014).

Because of likely similarities across the Holarctic region in how benthic macroinvertebrates respond to environmental gradients, we presume the findings described above hold for taxa that evolved in the Columbia River basin. In the Pacific Northwest, many benthic macroinvertebrates rely on cool, flowing streams and rivers for their habitat. In fact, stream temperature is thought to be the "master variable" affecting the life-history strategies of most aquatic macroinvertebrates in the Columbia Basin; development rates, metabolism, and feeding of aquatic macroinvertebrates are highly affected by water temperature (ISAB 2011).

The Washington State Habitat Action Plan (2015) assessed the vulnerability of different taxa of benthic macroinvertebrates to climate change impacts. In general, mayflies were predicted to have a lower vulnerability, while stoneflies and caddisflies were predicted to have a higher vulnerability. For example, *Goreilla baumanni* (a caddisfly) was placed on a "climate watch list" due to its high vulnerability. These caddisflies use headwater habitats during their larval and pupae stages, and this link to a specialized habitat makes them especially vulnerable because these areas may be more likely to dry out. Stoneflies of the *Lednia* genus were also placed on this watchlist because their habitat preferences are centered around high-elevation coldwater locations, which may warm significantly in the future, especially as glaciers recede.

Another important distinction to make when evaluating macroinvertebrate vulnerability is whether taxa are fully aquatic (e.g., gastropods, crustaceans, etc.) and therefore exposed to water temperature year-round, or semi-aquatic and therefore able to escape extreme water temperatures after emergence, with emergence from the aquatic phase hypothetically arriving earlier with climate change (Plotnikoff pers. com. 2017). Because many of the aquatic habitats in the Columbia basin are already in a disturbed state, a high proportion of benthic macroinvertebrate assemblages may be weighted towards taxa with wider physiological tolerances to environmental degradation. Ironically, it may therefore be more difficult to detect climate-induced changes to tolerant assemblages in these degraded habitats, since members of the biotic assemblage can withstand exposure to environmental gradients that would be detrimental to more sensitive taxa (Plotnikoff pers. com. 2017). A recent analytical approach developed by

Hawkins and Yuan (2016) shows promise for evaluating the sensitivity of individual taxa to human disturbance, based on observed taxa-specific increases or decreases in abundance as compared to an expected reference condition.

Biotic Interactions

Benthic macroinvertebrates form an important part of the lotic food web, consuming organic matter and nutrients from the riparian forest and in-stream primary production thus representing a critical transformative food-web link for fish and other insect predators (ISAB 2011; Sullivan and White 2017). Benthic macroinvertebrates also contribute many other important services in freshwater ecosystems, including the conversion of organic material into food for other organisms, nutrient cycling, and the aeration of sediments. The loss of species diversity can reduce these ecological benefits (Covich et al. 1999). Climate change affects macroinvertebrates throughout their "ecological hierarchy" including changes to physical emergence, development, migration, reproduction, and the timing of resource consumption (Prather et al. 2009). Higher temperatures can disrupt the interactions between species through changes in phenology, survival, symbioses, and other pathways (Traill et al. 2010).

Climate change is expected to affect riparian plant communities through changes to air temperature and hydrologic-geomorphic regimes (Meyer et al. 1999; Bendix and Hupp, 2000). Resulting changes to benthic macroinvertebrate assemblages are expected following climate-induced changes to plant growth and subsequent shifts in hydrology (Suren and Riis 2010). However, some traits such as high crawling rate and armoring may buffer the response of certain benthic macroinvertebrate taxa to extreme low-flow events induced by climate change (Walters 2011). In Northern California streams, a commonly-applied index of biotic integrity (IBI) was not sensitive to climate-related changes, but using a trait-based approach revealed that macroinvertebrates with a life cycle >1 y and body size >40 mm declined with increasing temperature or decreasing precipitation. These collective findings indicate that a trait-based approach may provide more sensitive indicators for the effects of climate change on benthic macroinvertebrate assemblages.

In general, there is a lack of understanding about how the loss of global invertebrate species may affect ecosystem services (Prather et al. 2009). Information is lacking about the diversity of most freshwater macroinvertebrate assemblages, but high levels of local endemism and species richness are typically found (Balian et al. 2008). Better monitoring and understanding of aquatic food web structure and function is needed to understand the effect of climate change on stream biota and to prevent losses of macroinvertebrate populations (ISAB 2011; Wisseman and Johannes 2015).

The presence of salmon carcasses in natural streams increases macroinvertebrate density and biomass because of the greater availability of nutrients and organic matter (Janetski et al. 2009). Warmer water temperatures predicted with climate change are expected to negatively influence the abundance of salmonids (Justice et al. 2017; White et al. 2017), thereby impacting the abundance and potentially assemblage structure of benthic macroinvertebrates through the loss of spawner carcasses as a marine-derived nutrient subsidy (Wipfli and Baxter 2010).

Habitat Connectivity

Benthic macroinvertebrates benefit from stream habitat connectivity that exist on a continuum, where migration is possible upstream or downstream. This habitat connectivity is limited, however, by the ability of individual species to migrate, as defined by their ability to drift downstream or—after emerging as adults—fly upstream to establish new habitats. Wisseman and Johannes (2015) examined the potential impacts of climate change on freshwater macroinvertebrates of the Deschutes, Klamath, and John Day basins of eastern Oregon. They found the most vulnerable habitat types to be in the alpine/subalpine streams and wetlands and forested headwater streams and springs. The macroinvertebrates associated with these habitats tend to have a lower adaptive capacity and upward migration as a response to warmer temperatures is limited because of their headwater locations. Streams that become ephemeral or are severely disrupted also limit the connectivity of macroinvertebrate assemblages, which may become trapped there and placed at risk of extirpation. Macroinvertebrate assemblages highly adapted to springs in Switzerland were likewise predicted to suffer from climate change (von Fumetti et al. 2017). In the semi-arid west, connectivity may also be considered as thermal refugia and the availability of water connecting these refugia. Climate change may impact this connectivity through increases to groundwater temperatures, and changes to summer stream flows as it relates to upwelling (Plotnikoff pers. com. 2017).

Hogg and Williams (1996) performed an experimental water temperature increase in a headwaters channel near Toronto, Ontario in order to study the effects on stream macroinvertebrates. They found that temperature increases stimulated the growth rates of macroinvertebrates but suppressed their overall abundance. They also found that macroinvertebrate life history parameters were even more sensitive to gradual changes in water temperature than their abundance and density, and advocated for maintaining diverse, connected habitats in order to facilitate gene flow among macroinvertebrate populations and reduce their vulnerability to climate change. Domisch, et al. (2011) modelled the susceptibility of stream macroinvertebrates in a submontane region of Central Europe and found that a changing climate will likely alter the range of these species along the river continuum, with possible effects including a loss in population abundance and diversity in headwaters areas, and the establishment of non-native macroinvertebrates in lower reaches.

Human activities that disrupt the continuity of river systems may also have a profound effect on stream macroinvertebrates (Vannote et al. 1980), especially when climate change is expected to increase demand for electricity derived from hydropower. The establishment of benthic macroinvertebrates is hindered in river reaches where hydroelectric dams alter natural flow patterns and cause daily and seasonally fluctuating water levels, and reduced flow velocities can favor non-native macroinvertebrates (ISAB 2011). Kennedy et al. (2016) found that hydropeaking regimes —with discharge often varying by a factor of 10 or more per day to meet energy demands—can lead to extirpation of aquatic insects that lay eggs near the river edge, a common life history strategy for many taxa including ecologically-important mayflies. White et al. (2017) examined the relationships between stream flow, temperature and macroinvertebrate responses in impounded river in the UK. They found macroinvertebrate assemblages to

be particularly sensitive to changes in extreme flows in these regulated systems. Other human activities including land use and agriculture creates thermal barriers, diminished water recharge, and changes in the timing of flow in Columbia River Basin streams and rivers.

Adaptive Capacity

The adaptive capacity of macroinvertebrate assemblages (and individual taxa) will be an important factor in how resilient they are to climate change impacts. Knowledge of baseline macroinvertebrate assemblages in the Pacific Northwest pre-European settlement period is lacking (ISAB 2011). Anthropogenic effects of the development of the Columbia River and its tributaries since the 1800's include increased sedimentation, slower flows, greater water depths, and higher summer water temperatures, which have all contributed to drastic changes to benthic macroinvertebrate assemblages. Many native benthic macroinvertebrates have been extirpated or decreased in abundance (ISAB 2011). Wisseman and Johannes (2015) identified the different classes of macroinvertebrates with the highest and lowest adaptive capacity to climate change in Eastern Oregon basins, with eurythermal (able to tolerate a wide range of temperatures) species likely having the highest adaptive capacity, and those species associated with snow-melt and glacier-fed habitats to have the lowest adaptive capacity.

Resource managers should embrace practices that help to understand and assist the adaptive capacity of benthic macroinvertebrates. In general, ecosystem function is more resilient to disturbances when species diversity or key functional groups of species are maintained (Traill et al. 2010). Prather et al. (2009) made several recommendations for researchers and managers regarding macroinvertebrate protection and climate change: (i) Research macroinvertebrate ecosystem services; (ii) perform interdisciplinary research; (iii) Conduct biomonitoring of macroinvertebrate assemblages to monitor changes ; (iv) Initiate informed decisions with stakeholders and policy makers; and (v) Increase public awareness of the role macroinvertebrates play in ecosystem service managers (i.e. through local schools, parks visitors and media).

Other Interacting Stressors

Several other stressors acting individually or synergistically on benthic macroinvertebrates assemblages may compound the impacts of climate change. These include:

- Use of pesticides/persistent toxins in landscape;
- Land use practices in the riparian zone and hillslopes (e.g., logging, grazing, ranching, road building);
- Degradation of physical in-stream habitat and floodplains;
- Increasing exposure to wildfires; and
- Increasing population density, intensified by climate-driven human migrations.

Table 1. Climate vulnerability assessment for benthic macroinvertebrates assemblages (BMAs) in riverine ecosystems of the Columbia River Basin.

Key Factor of Vulnerability	HABITAT SUITABILITY: To what extent will climate change alter habitat suitability affecting exposure, sensitivity, and adaptive capacity?	BIOTIC INTERACTIONS: To what extent will climate change influence competitor, predator, and prey/resource interactions?	CONNECTIVITY: To what extent will climate change alter the degree of connectivity to larger networks of populations or suitable habitats?
Climate-related questions to consider	• Are stream temperatures expected to remain or become unsuitable? • Are streamflow conditions (peak, low flow, seasonality) likely to become unsuitable? • Could changes in human water use act synergistically with climate change (e.g., de-watering, diversions, hydropeaking)? • What is the adaptive capacity of BMAs to climate change impacts on physical habitat? • Are there stressor thresholds to habitat, which when surpassed, will cause BMAs to shift or decline? • Will increased storm intensity increase pollution, turbidity stressors? • Will food quality decrease in carbon enriched atmosphere?	• Will climate change adversely affect predation on BMAs? • Will climate change adversely affect prey or resource availability to BMAs? • Will climate change adversely affect competition or other adverse biotic interactions within BMAs? • How will climate-induced range shifts of invasive species impact BMAs? • Will climate-induced reductions in salmon populations affect nutrient availability/food webs in tributaries? • Will spatial/temporal phenologic mismatches harm predator/prey relationships?	• Are BMAs currently isolated, or connected to larger networks of populations and habitat? • Will this connectivity remain as a result of climate change? • Are human-caused barriers (culverts, diversions, dams, etc.) present that could become barriers to BMAs under changing stream flows? • Will extreme climatic events (e.g., drought or flooding) increase the degree of isolation of BMAs? • Will BMAs have sufficient thermal refuges, which occur at finer scales than fish?
Assess Vulnerabilities	A-Habitat likely to remain or become suitable B-Habitat likely to become marginal (i.e., at or near thresholds) C-Habitat likely to become unsuitable	D-Threats from biotic interactions likely to be low E-Threats from biotic interactions likely to be high	F-Assemblages likely to be connected to a larger network G-Assemblages likely to remain or become isolated
	Answer: **B**	Answer: **E**	Answer: **G**

The Table 1 matrix was developed based on selected literature and expert knowledge of current conditions and expected impacts of climate change on benthic macroinvertebrate assemblages. It is important to note that while the process required deterministic answers to "Assess Vulnerabilities," the reality is likely to be more nuanced. While habitat suitability will likely become marginal for many assemblages, some habitats will also likely become unsuitable. Regarding connectivity, while many assemblages will likely become isolated, many others will likely remain connected to a larger network. In producing the matrix of strategies in Step 2, we considered these nuances.

Step 2: Climate Adaptation Strategies

In Step 2, the CBPF's Decision Support Framework was utilized to calculate the overall vulnerability of Columbia River Basin benthic macroinvertebrate assemblages to climate change impacts, and to develop summary goals and strategies for their survival and continued resilience.

Table 2. Climate adaptation strategies derived from vulnerability matrix (Step 1).

Relative vulnerability to climate change:	Medium-High
Relative value for stream macroinvertebrate conservation:	High value in the short and long term, but may require investment to remove invasive predators or competitors and adjustments to land management practices
Potential goal:	Identify and protect existing high quality habitat while improving the suitability of the entire stream network (including degraded habitats) to support resiliency of stream macroinvertebrate populations
Strategies:	• Protect existing climate refugia and networks; • Moderate stream temperature increases; • Moderate base flow decreases; • Moderate changes to peak flow timing and magnitude; • Remove/suppress invasive predators and competitors; • Prevent invasion of non-native predators and competitors; • Adjust land use practices that work synergistically with climate change; • Reduce uncertainty through research and monitoring; • Determine additional strategies after clarifying management goal(s)

Step 3: Climate Actions

In Step 3, we employed the approach of the CBPF Template for Decision Frameworks to select a set of objectives and actions that respond to the Climate Adaptation Strategies developed in Step 2. This list of actions was further refined to ensure that they are appropriate to the challenges and opportunities to climate mitigation of benthic macroinvertebrate communities of the Columbia Basin. Nevertheless, these actions, summarized in Table 3, do not apply to specific geographies or communities, and should only be considered as a general example for resource managers.

Table 3. Climate adaptation objectives and actions derived from decision support framework (Step 2).

Strategies	Objectives	Actions
Protect existing climate refugia and networks	• Identify and protect areas likely to remain climatically suitable over the long-term • Protect and restore critical or unique habitats that buffer survival during vulnerable periods (i.e. seasonally or at particular life history stages)	• Understand and map where tributary confluences and groundwater inputs may buffer projected stream temperature increases • Protect/restore off-channel habitats, spring brooks, and seeps • Protect/restore flood or thermal refugia and stream segments that are important as connectors
Moderate stream temperature increases	• Reconnect floodplains • Restore incised (widened) channels • Restore stream flows • Maintain/enhance riparian vegetation to shade streams	• Resolve thermal barriers • Reconnect floodplain features (e.g. side channels, ponds) • Designate and restore natural floodplain boundaries • Remove infrastructure (e.g., roads, levees, rip rap, etc.) from floodplains • Reintroduce beaver or build beaver dam analogs to increase sediment storage • Work to restore natural flow regimes • Reduce water withdrawals, restore summer baseflow • On regulated streams, pulse flows during critical times, sourcing from lower in the thermocline • Reduce grazing pressure (e.g. reduce stocking rates, use rest-rotation systems, fence riparian areas, provide off-stream water sources, retire vacant allotments in priority areas, increase monitoring in priority areas to ensure good practices) • Restore riparian vegetation in degraded areas • Adjust riparian vegetation to favor species that are better suited for future climate conditions
Moderate base flow decreases	• Restore or replicate natural stream flows • Reduce water withdrawals and/or water diversions • Restore riparian and hillslope vegetation • Increase natural water storage in groundwater aquifers	• Remove or breach dams • Increase water storage of water in floodplains by encouraging natural flooding and groundwater infiltration • On regulated streams, pulse flows during critical times, sourcing from lower in the thermocline • Increase efficiency of irrigation techniques • Explore potential to combine sprinkler and flood irrigation to capture increasing spring floods (and recharge groundwater supplies) and then switch to more efficient sprinkler irrigation when stream flows are lower • Consider alternative water supplies for public land operations to retain in-stream flows • Legally secure water rights/agreements for in-stream flows • Reform water laws to enable increased acquisition of in-stream water rights • Explore the use of water trusts/funds to increase investments in the protection of watershed health and function • Use water pricing to encourage water conservation • Establish native riparian vegetation • Remove non-native riparian vegetation

		• Reintroduce beaver and/or install artificial beaver-mimic dams where compatible with conservation goals • Increase off-channel habitat and protect refugia in side channels • Protect wetland-fed streams which maintain higher summer flows • Maintain/restore forest and wetland vegetation cover • Reduce road density
Moderate changes to peak flow timing and magnitude	• Restore floodplain connections • Restore incised (scoured) channels • Restore riparian vegetation • Restore stream flow regimes • Reduce rain-on-snow flooding	• Remove infrastructure (e.g., roads, levees, rip rap, etc.) from floodplains • Reconnect floodplain features (e.g. channels, ponds) • Create new or restore degraded floodplain habitats • Reintroduce beaver to encourage dam-building that increases sediment storage and deposition • Establish riparian vegetation; remove non-native vegetation • Remove stressors that cause riparian damage (illegal or degraded trails, cattle, etc.) • Disconnect road drainage from streams • Restore natural drainage systems, create retention ponds • Maintain/restore forest, wetland and riparian vegetation cover
Remove/suppress invasive predators and competitors	• Remove/suppress invasive predators and competitors	• Remove or control invasive predators or competitors (via electrofishing, chemical removal, genetic swamping) • Encourage increased harvest of non-natives
Prevent invasion of non-native predators and competitors	• Prevent non-native predator invasions • Restore habitats that convey an advantage for native species over non-native species	• Strategically use physical or electrical barriers to prevent further spread of non-native species • Model future changes in stream flow and habitat to anticipate future invasion hotspots • Promote expansion native populations in areas where trying to prevent invasion of non-native species
Reduce uncertainty through research and monitoring	• Monitor changes in aquatic food web dynamics • Enhance research and monitoring to better understand the current status of macroinvertebrate communities and their vulnerabilities to climate change • Communicate science about macroinvertebrate communities to the public	• Assess food webs for baseline data; monitor food web dynamics in space and time • Research key questions related to climate change impacts on macroinvertebrate communities *(For examples, see Table 1, climate-related questions*) • Expand research of macroinvertebrate ecosystem services • Perform interdisciplinary biomonitoring of macroinvertebrate assemblages to monitor changes • Increase public awareness of the role macroinvertebrates play in ecosystem service managers (i.e. through local schools, parks visitors and media).
Determine additional strategies after clarifying management goal(s)	• To be determined	• To be determined

The objectives and actions listed in Table 3 focus primarily on protecting and restoring the coldwater stream habitat that is important to macroinvertebrate communities. Habitat actions can be designed to assist macroinvertebrate taxa that cannot escape a changing aquatic environment. Any effort at habitat preservation should include unique habitats such as groundwater upwelling zones or tributary confluences, which will offer a refuge under future climate conditions (Plotnikoff pers. com. 2017). The current condition of riparian vegetation also needs to be taken into account when considering the effects of climate change. Riparian vegetation provides stream shading and organic litter inputs, improving the species composition and production of aquatic macroinvertebrates (Vannote et al., 1980; ISAB 2011). Floodplain management and connection to thermal refugia are also important opportunities for stream habitat protection and restoration. In addition to stream habitat actions, changes to water management, basinwide land use, suppression of invasive species, and research and monitoring are highlighted in the range of helpful objectives and actions.

Data Sets

Many regional fish habitat programs collect benthic macroinvertebrates as part of ongoing habitat monitoring (Table 1), and maintain regional datasets of their distribution, abundance, and diversity. As programs increasingly adopt the Northwest Standard Taxonomic Effort (NWSTE) guidelines (https://www.pnamp.org/project/4210), data can be shared widely across the region.

Table 3. Type of macroinvertebrate samples collected in common fish-habitat programs of the Pacific Northwest (from Sullivan and White 2017).

Program	Abbreviation	Targeted riffle	Reach-wide	Multi-habitat	Drift
USFS-BLM Aquatic and Riparian Effectiveness Monitoring Program	AREMP[1]	X			
California Department of Fish and Game	CDFG[1]	X			
EPA Environmental Monitoring Assessment Program	EMAP[1]	X	X		
National Aquatic Resource Surveys	NARS[2]		X		
USFS-BLM Biological Opinion Effectiveness Monitoring Program	PIBO[1]	X			
Upper Columbia Monitoring Strategy	UC[1]	X			
Columbia Habitat Monitoring Program	CHaMP[3]				X
BPA Action Effectiveness Monitoring	AEM[2]	X		X	
BLM AIM-National Aquatic Monitoring Framework	AIM-NAMF[2]	X	X		
USGS National Water-Quality Assessment	NAWQA[2]	X			
Status and Trends Monitoring for Watershed Health and Salmon	WA[2]		X		
Oregon Department of Environmental Quality	ODEQ[2]	X			

[1] Reviewed in (Roper et al. 2010)
[2] Pers. comm. (various sources). NARS is an outgrowth of EMAP.
[3] CHaMP 2016

Additionally, the following data sets will be helpful in assessing the likely future impacts of climate change on water temperature and flow in Columbia River Basin streams and rivers:

NorWeST Statistically Modeled Historic and Future Stream Temperature Data

Isaak, et al. (2015) developed spatial statistical network models of summer water temperatures using historic measurements collected in the NorWeST database and a series of other climatic and geomorphic data. They used these models to produce simulated August mean water temperatures throughout the Pacific Northwest for a range

of historic years (1993-2011), and for the future climate change periods based on the A1B emissions scenario of the CMIP3 global assessment.

Regional Joint Monitoring Operating Committee (RMJOC) II Streamflow Projections for Future Climate Change Scenarios (expected to be complete in June 2017)
This multiyear project will provide an updated set of streamflow projections for the streams and rivers of the Columbia River Basin for future climate change periods based on the most recent (CMIP5) global climate scenarios. The projections are a result of a modeling effort by the University of Washington with the VIC Hydro Model, which is supported by BPA and a regional consortium.

The Ambient Biological Monitoring Program dataset (1993-2004) from the Washington State Department of Ecology is a long-term monitoring project to explore spatial and temporal trends in benthic macroinvertebrate communities. It is available as a diagnostic tool for identifying stressors to macroinvertebrates and the settings in which they occur.

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