Predicting Climate Change Impacts on Aquatic Ecosystems across the Pacific Northwest

Webinar Transcript

Speaker:
Clint Muhlfeld
USGS, Northern Rocky Mountain Science Center, Glacier National Park

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Ashley Fortune-Isham: Good afternoon from the U.S. Fish and Wildlife Service's National Conservation Training Center in Shepherdstown, West Virginia.

My name is Ashley Fortune Isham. I would like to welcome you to our webinar series held in partnership with the U.S. Geological Survey's National Climate Change and Wildlife Science Center.

The NCCWSC Climate Change Science and Management webinar series highlights their sponsored science projects related to climate change impacts and adaptation. It aims to increase awareness and inform participants like you, about potential and predicted climate change impact on fish and wildlife.

I'd like to welcome Shawn Carter to introduce our speaker. Shawn.

Shawn Carter: Thanks Ashley. Today it's my pleasure to have Dr. Clint Muhlfeld with us. He's a Research Assistant Ecologist at the USGS Northern Rocky Mountain Science Center in Glacier National Park, and Research Assistant Professor at the University of Montana's Flathead Lake Biological Station.

Clint's involved with numerous interdisciplinary ecological studies focused on a variety of regional, national, and international aquatic research issues of growing importance to both society and biodiversity conservation. His applied research aims to assess the threat of invasive species, habitat loss, and climate change on native aquatic species and habitats in the Rocky Mountains of the U.S. and Canada in the Pacific Northwest.

And today he's going to be talking about some of his work. So it's my pleasure to introduce Clint, and it's over to you.

Clint Muhlfeld: Thank you so much, Shawn. It's my pleasure to talk to you today about our climate change research in the northern Rockies and the Pacific Northwest. I changed the title of my talk today to include other biota besides salmonids because we're doing a lot of high-alpine research on rare bugs below melting glaciers which I'll also discuss. So the title of my talk today is, "Predicting Climate Change Impacts on Aquatic Ecosystems across the Pacific Northwest."

We know that climate change has impacted every centimeter of the Earth, and especially, in the western United States. It's no exception here. This landscape is undergoing tremendous change in the thermal and hydrologic nature of stream and lake environments. And so the goal of our research is to really provide tools and a good understanding of how climate change may or may not impact different species, how these impacts may be realized at different scales, so we can predict and then manage for these potential outcomes into the future to build resiliency and adaptive capacity for aquatic ecosystems. Specifically a lot of our research has focused on how hydrologic, thermal, and habitat change has already influenced and may influence native trout and salmon in the Pacific Northwest.

We're going to talk today about applying new techniques that we've developed for combining climate data with fine-scaled vulnerability assessments using genetic data, habitat analyses, and wrapping this up to understand more holistically these processes and how they affect species for adaptive management and conservation. Understanding how climate change may impact aquatic ecosystems is obviously a major priority for conservation management. Changes in species ecology associated with climate change has been documented and predicted for a broad range of organisms, especially salmonids.

Now, salmonid fish may be at particular risk of climate warming because they're ectothermic. They are cold-water-dependent. They have a really narrow thermal range. Their life history events are adapted to the timing and magnitude of stream flow events. And their dispersal patterns are restricted to stream networks. They've really nowhere to go. Moreover, they have enormous economic, ecological, and cultural value.

I'm going to start the story today at the top of the continent. It's the head waters or the water storage or water tower of the Columbia Basin system. It's called the "Crown of the Continent." This is one of the most biodiverse and ecologically intact systems in North America. It's the convergence zone of four bioclimatic regions converging on the narrowest point along the Rocky Mountain chain. With waters flowing to the Hudson, Atlantic, and Pacific Oceans. It's clearly the water tower of the continent.

We've been trying to understand the effects of these warming impacts across these landscapes, starting where the glaciers originate up in Glacier National Park and understanding how those aquatic communities are impacted immediately below these melting and disappearing glaciers -- understanding these impacts all along the continuum, down to these valley bottoms where the fish roam, where there's a host of biodiversity, not only within the surface water of channels but out into the flood plain zones where there's a host of other organisms that are...some aren't even described.

This area provides really complex cold and clean areas for growth, survival and persistence of a variety of species. It's relatively intact and the water quality is impeccable. It's very cold, nutrient-poor, and again, this is the water that originates at the apex of the continent and flows downstream providing oxygen and really cold water for fish to spawn in, grow, and survive in.

Today, I'm going to be talking to you about the impacts of climate change on trout populations in the headwaters of the basin, and then I'm going to move downstream and talk about some of our vulnerability work on salmon and steelhead populations as well. Here, in the top of the continent, in the top of the Pacific Northwest, it's considered a range-wide and regional stronghold for a variety of species that have survived cataclysmic changes to the environment, such as wildfire, floods, glaciation, et cetera, for at least 12,000 years.

We have the westslope cutthroat trout, these rare stoneflies existing below these melting glaciers in the high country and threatened bull trout, which are listed under the ESA. The bull trout is a charismatic megafauna of the aquatic realm. It's an apex predator. It requires large connections of impact habitats to complete its life history. It migrates. It's essentially an inland salmon. It migrates 250 kilometers right back to the stream they are born in. The juveniles rear one to four years before emigrating out to the main stream where they grow to maturity to complete their life's history. These guys are great indicators of aquatic health, because not only do they require intact and connections of habitats, but they also have the coldest water requirement of any salmonid species in the Pacific Northwest.

Similarly, westslope cutthroat trout are an excellent indicator species in the face of warming climate. Unlike bull trout that spawn in the fall, they're spring spawners, so they're using high flows to ascend the stream network back to their native streams. They're spawning in a little bit higher gradient higher up in the watershed system than bull trout. The embryos incubate in the stream gravels into the summer months before they emerge. Just like the bull trout they exhibit migratory life histories as well as resident life histories where they remain in their stream their entire lives. These salmonids have adapted to a changing climate for at least 12,000 years.

When the glaciers were receding, these species have invaded and colonized these areas for many, many different times throughout our geologic history. At the end of the last glacial period, the Wisconsin, we've seen bull trout and cutthroat occupying a variety of habitats. During the colder periods it's likely that these populations resided more in the valley bottoms. These were the sources for connectivity and dispersal, and the headwaters were more like sinks. When we had periods of extreme warming, for example, seven to nine thousand years ago, it's likely that those valley bottoms were the sinks and the sources were the headwaters, because these trout had to retreat to these colder stream networks located in the headwater areas.

My point here is that these species have adapted to persist under a changing climate for thousands and thousands of years before humans were on the landscape. However, over the past century-and-a-half salmonid populations and a lot of other aquatic biota have declined dramatically, largely due to habitat loss, degradation, fragmentation, invasive species resulting in competition predation, invasive hybridization, disease, and parasites.

It's the combination of these existing stressors and the exacerbating impacts of climate warming, which we're all concerned about, to build resiliency in our native trout and salmon populations throughout the Pacific Northwest. Understanding the past and how as a prelude to the future is really key to understanding the impacts of climate warming on aquatic species.

Just looking at real data over the last 100 years, we looked at air temperature trends in Western Montana, and we found that over that record a loss of about a month of extremely cold days and a three-fold increase in the number of hot days. The kicker here was the Northern Rockies. You think of this area as a refugium from climate because it's high and cold and there's a lot of snow and glacial masses, but these air temperature trends were tracking the global trend of increasing air temperatures. The main point here is that we're warming at two to three times the rate of the global average.

This landscape is undergoing dramatic change. The warmer air temperatures are decreasing our snowpack and our glacial masses are receding. We're seeing increasing disturbance events such as wild fires throughout the West. These changes are altering the hydrologic regimes of our stream and lake networks. Overall, we're seeing a decline in stream flows across the Pacific Northwest and the Northern Rockies. Several recent studies, shown here, have shown that the annual discharges had declined over the past several decades.

These flow regimes are shifting and changing. Here's an example of the Flathead river where positive values indicate increasing flows, negative values indicate decreasing flows. As you can see here, since 1958 on the shoulder months of the winter period, we're seeing the snow turn to rain. We're seeing increase in fall and winter fawning mostly on the shoulder months of the winter. We're seeing an earlier spring freshet, in general, about two to three weeks earlier. That's leading to reduction in stream flows during the summer months.

Here is a depiction of the hydrograph. We see high flows in the spring. We're seeing a shift to the left. A decrease in terms of the magnitude. Here is a spike in the fall. It shows a fall flooding event that nearly matched the preceding high flow associated with the runoff. Summer discharges are declining as I mentioned before, throughout several USGS gage stations in the Western United States namely in the Pacific Northwest. That's a general statement. There are different changes elsewhere but, in general, stream flows have declined.

Associated with that, temperatures are also increasing. So we've seen a steady increase in water temperatures across these stream networks for the past several decades. Perhaps, most iconic about the combining fact that changes in flow and temperature and melting snow masses is the melting glaciers in Glacier National Park. It's kind of the poster child of climate change. At the last little ice age in 1850, there was approximately a 150 glaciers on the landscape. Glacier's losing its glaciers. Now, there's only 25 named glaciers in Glacier National Park.

The most conservative climate change estimates show that all these glaciers will be gone by 2030. Glacier Park will no longer have its glaciers by 2030 based on the best available science. We're trying to understand these impacts across these landscapes at different scales. We're setting up a lot of different monitoring networks for stream temperatures such as the NorWeST Program in the Western United States. We're trying to understand how stream temperature is responding and how these ectothermic organisms are responding to a changing temperature and flow regime.

This example here shows our stream networks and the head waters of the basin where we have nearly 950 sites. We're developing both seasonal and daily temperature models to understand impacts on species over different scales. These include covariates such as land cover, ground water influences, elevation, and glacier and lake effects. Scale matters when understanding temperature responses over large and small areas throughout the landscape.

Landscape models are really important to understanding patterns and processes over large time and space scales. They're really important for integrating these changes into ecological and management issues for scenario planning and adaptive management, so scale definitely matters. But time does as well. That's commonly overlooked. We substitute space for time in a lot of instances. Whether that's right or wrong, we're trying to understand more about the temporal dimensions of climate change and the impact in aquatic systems.

We can understand over core scales and develop these monthly and seasonal models to understand average conditions, how these systems are changing, and link them with climate simulations to predict where across broad landscapes this change will occur. But there's also a need for these fine scale assessments of using daily models to then link with daily models of climate change to understand how species key components of the life's history are responding, such as life history traits in terms of shifting in the timing of spawning, fry emergence, growing days and incubation days. I believe that these different scales, these temporal scales are complementary in understanding the impact of climate warming on the thermal dynamics and response of the species.

Here you can see our stream temperature projections for August compared from the baseline to an RCP 4.5, which is kind of a conservative, middle of the road climate change forecast. As you can see here, we can understand and predict down to 30 meters, actually, potential stream temperature changes across the networks. We can then understand how critical thresholds may be exceeded under different climate warming scenarios.

We can also use these data to understand the relative change across these landscapes, so it's not just about the threshold, because of what areas are going to change the most over a given amount of time. As you can see here, the lower valley bottom, the major forks of the Flathead are predicted to change the most over the next several decades. Then we can move to a daily time step, as shown here with Leslie Jones' work, where she's developed these seasonal based models. Now we're going to a daily time step, the real data. The empirical data are shown here and the black circles show our predictions. As you can see, they match pretty well. Then we can link these daily time step climate simulation modeling data with key components of life history and development of trout and other aquatic organisms in the system.

One way we've done that is to apply to critical habitat for bull trout in this example. We've looked at both critical foraging, migrating, and overwintering habitat in the main rivers. Then these key spawning and rearing areas, where they go right back to spawn and the juveniles rear in. This paper came out this year, and what we found is we use our stream temperature models to predict stream temperatures across these different types of habitat. What we've found is that bull trout really occupy the very coldest places of the landscape. We can then use these different temperature thresholds to then understand and predict better how these habitats are going to change into the future, so we can inform management.

In this case, if you increase, under this model scenario, if you increase the stream temperatures one degree, we can expect more loss of habitat in these critical river corridors that they use, especially during the summer months, to ascend and spawn in their native trips. Then we can take that out over different time steps. We can then scale up to the scale of the crown. We've done that by looking at critical thresholds, such as 11 degrees, and then understand how that's going to potentially impact bull trout in the upper Kootenai system, in the Flathead system, and then over in the Hudson as well, the south Saskatchewan. And then look at the relative change across the landscape to then be able to prepare managers where we're going to see this change the most over the coming decades.

Obviously, with these analyses, high elevations, northern latitudes, and groundwater in glacial influence reaches are going to be really important. We're seeing a lot of warming in the lower elevations, in the lower latitudes. These areas in the northern regions, in the high elevations, are going to provide more thermal refugia. But, at the local level there's still spatial heterogeneity going on. We've been tracking bull trout to their known spawning areas and what we've found, over time, is these unconfined alluvial valley reaches are really important for bull trout spawning. At the reach scale, they're going back to these alluvial valley bottoms where there's a lot of groundwater and surface water interaction. There's, essentially, huge upwelling zones providing really cold temperatures in the summer and nutrients and well oxygenated water for the embryos to survive in.

We've set up temperature sensors throughout the flood plain and into the main channel. As you can see here, there's a great degree of diurnal temperature fluctuations in these bull trout spawning areas elsewhere. But you can see here, there's groundwater influence. On an average, these areas are almost two degrees colder during the summer months. These are likely areas that are going to be thermal refugia in a warming climate. However, these areas, because they're unconsolidated substrates, because they're multi-channel habitats, the incidence of winter flooding may scour these reds. That's another concern, into the future, that we need to learn more about.

It's not only about the temperature. It's about the flow too. If they're building these nests in areas that are susceptible to scouring effects associated with fall and winter flooding, like I showed you before, they could be vulnerable to those impacts other than temperature alone. We've been trying to understand not only how contemporary patterns are influenced by climate, and other human impacts, but how can we use the past as a prelude to the future. Can we use real data to then understand the relative influence of climatic variation on fish populations, in terms of abundance, distribution, genetic diversity, and phenology, and then build that into our climate projections so we can more accurately forecast climate effects into the future?

We just wrote a paper, a few years ago, focused on Rocky Mountain trout, using real data. Managers have been collecting fish population data for decades. Can we go into the archives and learn about the relative influence of climate and other human-induced stressors on fish populations? One example of that is our recent paper entitled, "Invasive hybridization in a threatened species is accelerated by climate change." This is the westslope cutthroat trout here. Like all other 12 extinct cutthroat trout species, hybridization is clearly the leading factor contributing to the decline of genetically pure populations. We need to figure out how climate might trigger expansion of hybridization in nature.

Hybridization, unlike a mule, where they're sterile. Hybrids produce hybrids. Hybridization spreads and eventually you might lose the genomic integrity of the species. That's really critical for conservation in the face of climate change because those locally adapted genes and gene complexes are a link to these locally adapted traits which have enabled these fish to adapt and persist in a changing climate. Once hybridization occurs, it breaks down those key linkages between the genes and their adaptive traits, or phenologies, on the landscape. With that, we might see their ability to adapt and persist greatly diminished in the face of climate change.

Building in the time component was really key, in this study, to understand how hybridization might spread in the face of climate change. What we did is we used temporal genetics data. Managers collected genetic data, back in the late 60s, early 70s, and into the early 80s. We used that to then resample areas in the 2000s to see if there's a change in hybridization. We found hybridization dramatically spread over just a few decades.

Despite, up until 1969, preceding these data right here, there was over 20 million rainbows stocked into the system. These are non-native introduced rainbow trout. There was 20 million stocked in the system. The only spot in the system, that we know of, that had high proportions of rainbow trout hybridization occurred in the lower valley bottom. This population here was essentially a time bomb waiting to go off under the right environmental conditions.

What we did is we resampled those areas. We found hybridization spread in nine of the 18 previously non-hybridized populations. Then we took a snapshot to look at the genetic integrity across the entire spatial extent of the stream network. We found this genotypic gradient with a lot of hybridization occurring in the valley bottom and a reduction in hybridization as you move away from the source.

We found, in some of these peripheral populations that we looked at...we actually used genetic techniques and paternity analysis to see if hybridization effects fitness in nature. What we found is as you increase the amount of non-native rainbow trout genes in female trout, in this example, in cutthroat trout, you see a dramatic reduction in fitness. With up to 20 percent non-native genetic admixture, or hybridization, with rainbow trout, we found nearly 50 percent reduction in fitness.

In the face of climate change, if there's a signal here, we can expect the resiliency and the adaptive capacity of cutthroat trout to be greatly reduced in a warming world.

We linked this with our high resolution stream temperature models, and then data from NASA, to reconstruct the invasion processes and the spread of hybridization over this time period. What we found is hybridization basically spreading into areas with reduced spring precipitation.

In general, the rainbows are spawning as flows increase in the spring and cutthroat are spawning on the descending limb or when flows are declining in the spring. What we think happened here is these high flows that we saw for decades kind of precluded rainbows from pioneering out into the river system. They kind of kept them abated because they're spawning as flows increase so those scour effects might wash away their nests, they might wash away their fry. They kind of prevented hybridization from spreading.

Again, 20 million rainbows were planted in the valley until 1969, until this happened. What we saw was a period of extreme drought, in the early 2000s, and a reduction in spring flows. This was likely a window of opportunity through which hybridization spread massively in the system, irreversibly corrupting the native genomes that have evolved over millennia in the system. To a lesser degree, stream temperature played a role as well. Rainbows typically have a little bit higher tolerance for maximum temperatures. We did find a correlation between increasing stream temperatures and the presence and the amount of hybridization.

These effects were realized in both our spatial models and our temporal models. I want to underscore here that the sources combined with the climatic variables were really driving the spread of hybridization here. As you moved away from the source vein, incidents of hybridization decreased. But it's the sources persisting on the landscape which then radiate out and hybridize and irreversibly corrupt these native genomes. We've showed this in a recent paper that's actually coming out tomorrow. It showed, in a very cold stream, we've got mean summer temperatures well less than 10 degrees in Langford Creek and a very hot stream...we saw hybridization increase over time.

What we did is we looked at the population dynamics using real data over several years. We found that despite the very strong selection against admixture, in both environments, hybridization increased over time due to the continued dispersal of rainbow trout from downstream source populations. If these sources persist, climate alone won't impede or prevent hybridization from occurring. It's just a matter of time where you get these dramatic changes in the environment, like those periods of extreme drought, that are conduits through which hybridization will spread in nature. It's a combination of these sources with the climate that might lead to the eventual loss of native cutthroat trout.

We're even studying effects of climate not only in the valley bottoms, where there's neighbor trout, but we're also studying them in the headwater areas below these melting glaciers. There's a couple different aquatic invertebrates, that are endemic to Glacier National Park, that have been petitioned for listing under the Endangered Species Act because of climate change induced threats. Unlike the polar bear that was listed, no other stream invertebrates have been petitioned except a couple in Glacier National Park.

We're trying to understand how the recession of the glaciers, the changes in these streams from perennial sources to more intermittent, and the stream warming, is effecting these bugs. It's squeeze play at the top of the continent. There's nowhere to go. These guys have been retreating upstream, tracking these cold waters, as the glaciers recede. They're confined to these 500 meter reaches, immediately below these melting glaciers, that are highly susceptible to change as these glaciers continue to recede. Like I said earlier, all the glaciers are predicted to be gone by 2030.

This is *Lednia tumana*. Joe Giersch is an aquatic etymologist studying these stream systems. This is the first footage of this ESA candidate species for listing because of climate warming. We did a broad scale habitat analysis using MaxEnt. We found that the highest probability of occurrence occurs in over 23 square kilometers of habitat across Glacier Park. If you take away the glaciers and the permanent snow masses, we'll see an 81 percent potential reduction in distribution. This species is strongly linked to glaciers. If the glaciers go, they're going to be highly threatened with extinction.

There's another species too, the *Zapada glacier*. We've found, using time series data collected back in the 1960s, where this species was confined to the Many Glacier area of Glacier National Park. This is in dew specimens. We were able to kind of reconstruct where people sampled this species back in the 1960s. Then we resample these areas over the past several years. We found a massive range contraction of this rare endemic invertebrate. You can see here, these two glacial basins within the Many Glacier system, you can see large tracks of glacial masses with massive recession over the past several decades. During the study period, these glaciers receded about 35 percent from 1960 to 2012.

Here's the historic distribution of the *Zapada glacier* as we knew it. We re-sampled these areas using morphology to identify the species, using DNA barcoding to find these cryptic species at the nymph stage. Joe did this over several years and found only one population remaining in their native range in the Many Glacier system, way up at the tippy-top of the continent. The summer temperatures increased over the study period; glaciers decreased by 35 percent. There's a strong correlation here between the loss of glaciers and a range contraction of this rare bug retreating in colder water. Here's where we know they occur. They're at the top of the continent. There's really nowhere to go. These might be some of the first species to go under climate change.

We're not only studying how species respond distributionally and over time and space, but we want to gain an understanding, too, of how their demography and genetic diversity plays into it. We worked with a variety of folks here, and we recently developed a framework that combines demographic and genetic factors to assess population vulnerability in strained species. My point here is that it's not all about distribution. There's important components of persistence we've got to think about. We've got to think about abundance. We've got to think about life history in diversity. We've got to think about genetic diversity which is the basis for evolution and adaptation in the face of climate change. We need to think about all these things when we're thinking about vulnerability.

This is a framework that combines demography and genetics to come up with different "demogenetic," we call it, indexes of population vulnerability. What this allows managers to do is you can put different resistant surfaces across a stream network, and you can forecast out to see how these changes in demography and genetic diversity will be realized under different climate change scenarios, or any kind of habitat use or invasive species scenarios as well.

You can see here in Generation 0 we can show the genetic and demographic integrity of these populations, and then give managers a glimpse at their future in terms of demography and genetic health. These are the kinds of things we need to build in our climate change predictions to better understand species' responses. We've learned a lot at the top of the continent, and we've been working on a grant with the Northwest Climate Science Center that has funded a lot of that work, as well as expanded it out to the Pacific Northwest.

We're also working with a group lead by Gordon Luikart from NASA, where we're scaling up to the Pacific Northwest to predict climate change vulnerabilities in salmon and in trout across this landscape. It's a huge landscape where these species have a freshwater phase of growth and they're migrating to the ocean to grow to maturity just like the bull trout in the inland Rocky Mountain region.

We wanted to not only look at patterns of distribution, but look at patterns of genetic diversity and how those relate to vulnerability. Vulnerability is defined as the degree to which a system is susceptible to adverse effects of climate as a function of exposure, looking at climate change, namely temperature and flow in this case, sensitivity, looking at habitat buffering potentials like the groundwater influence areas that I showed you with bull trout, and their adaptive capacity such as genetic diversity and their ability to cope with change.

We launched this study, first to focus on bull trout to understand how climatic variation influences both ecological and evolutionary processes. Very few studies have done this, have looked at how climatic variation influences genetic diversity across landscapes and over different time scales. We sampled 130 populations of bull trout throughout the Pacific Northwest to test whether patterns of genetic diversity were related to climatic variation. We then determined whether bull trout genetic diversity was related to climate vulnerability at the watershed scale which we projected into the 2040 and using existing habitat complexity data as well.

Here's an example of how we can look at the relative rankings of climate and habitat and genetic variables for watersheds occupied by bull trout. Here you can see that summer temperature, winter flood frequency, valley bottom habitats, those alluvial valleys I told you about, and allelic richness, genetic diversity here. You can see there's a strong gradient in genetic diversity as you progress up the system. Areas in the lower basin, they're warmer,on the fringe of the distribution, have less genetic diversity or allelic richness in this case. As you move up into the Columbia headwaters, there's a strong pattern of increased genetic diversity. Was this related to these patterns of landscape change in terms of both climate and habitat?

You can see here after accounting for the spatial pattern of this genetic diversity from down in the lower Columbia to the Headwaters with linear mix models, we found that allelic richness in bull trout populations was positively related to habitat patch size and complexity and negatively related to maximum temperatures and the frequency of winter flooding. There's a very strong correlation with genetic diversity and these climatic and habitat variables across the scale of the Pacific Northwest in terms of bull trout.

When we look at vulnerability in terms of exposure to temperature and flow plus the habitat buffering effects of these alluvial valley bottoms, we found that the average allelic richness was strongly correlated with those variables. We can anticipate in a future climate scenario that as things warm, these flows change, we might see their genetic diversity change still.

What was most of concern here is that we found in areas that are most vulnerable to change currently, are the areas with the least amount of genetic diversity. We can expect that as climate continues we'll see inbreeding effects, potentially, and the loss of adaptive capacity, potentially.

We're also expanding this work to look at salmon and steelhead as well. I just wanted to give you an understanding here of the scale we're dealing with both winter run and summer populations of steelhead. Alisa Wade and Brian Hand are working hard on this analysis now. We're also adding bull trout to the mix for this vulnerability assessment across the Pacific Northwest.

Looking at patterns of genetic diversity and how those correlate with climatic features. In the case of steelhead, we looked at these major evolutionary significant groups to see if there was a correlation with climatic variation and genetic diversity. We did find one. We found that winter precipitation, in this example, was strongly related to patterns of genetic differentiation. So there's a strong relationship between climatic variation and these patterns of genetic diversity in steelhead populations as well.

What we're doing is we're using vulnerability analyses to then look at how changes that are built on these empirical relationships, built on our hypotheses, built on real data and published data.

They're all hypotheses. All these vulnerabilities assessments are hypotheses-driven. But we know some of the things that are strong drivers of change like thermally suitable habitat, like run-off patterns, these valley bottoms, land use, critical habitat, and building in other things than just changes in occurrence or distribution, building in local abundance such as red trouts. We've collected tons of this data throughout these networks and combining them with patterns of genetic diversity, as I've discussed, as well.

This is our model for steelhead. We're doing this for each species across the Pacific Northwest. We can look at vulnerability in a lot of different ways. There's no really right or wrong way to do this. But in this case that Alisa provided, we looked at exposure in terms of changes in temperature and flow, so we have a spatially explicit temperature model that's linked to a flow model, VIC, to then predict that the watershed scale, the vulnerability of different habitats now and into the future.

We have habitat predictions across the network. We also are building in patterns of demography and genetics and understanding how these are going to change into the future. What it comes down to, and don't get caught up in this huge mess over here, these elements that we're including in vulnerability assessments greatly dictate the outcome. From these simple models that have been predicted or developed, we have exposure in habitat equals vulnerability. Here we're arguing that demography and genetics that are critical components of persistence, need to be built into these vulnerability assessments as well, and genetics, especially, where we find strong linkages.

As you can see here, if you build in demography compared to the simple approach verses genetics, you're going to get different answers depending on what you're looking at. Understanding thereal patterns in space and time, building that into these vulnerability in assessments, and then doing sensitivity analyses, looking at how climate variation might be sensitive to these changes as well as the different components of the vulnerability scores.

Finally, I wanted to let you know about a new project funded by the USGS in the Rockies where we're moving beyond the space-for-time models, where we're looking at that other temporal dimension that's so critical to look at in terms of determining the relative influence of climate variation on fish populations.

We're looking at using these high resolution daily stream temperature models, linking them up with real data that have been collected from the crown of the continent up in Banff and Jasper National Parks, all the way down through Glacier Park, down to Yellowstone, down in Wyoming, into Southern Colorado where we can quantify these relationships between climatic variation and demography and genetic integrity. Then we can look at how this change influences assemblages and the non-native and native species interactions over space and time.

To summarize, we've entered a new realm of disequilibrium in the 21st century. Our predictions show that these habitats will become more and more variable and shift. Some will decline or become intermittent. Many populations will adapt and track. Others won't. Combined with these existing stressors, many of these populations are already depressed and already have reduced resiliency in the face of climate.

Conservation needs will be real daunting and informed management is more crucial than ever in this changing world. But I'd argue that we have the tools necessary right now. Maybe not all of them, but we do have some. In many cases, it's back to the basics for informed decision making because management decisions now will have enormous effects on the amount of native aquatic biodiversity a century from now. We're on the critical point of conserving these species for future generations.

As Wayne Gretzky says, we've all probably seen this slide, “skates where the puck is going to be, not where it's been”. We need to look over broader time and space scales to understand species' responses for adaptive management because we're going to miss 100 percent of the shots you don't take. In the face of uncertainty, managers are going to have to make difficult decisions to try to keep some of these organisms on the landscape for future generations. We can do that through an adaptive framework where we're constantly identifying and prioritizing and learning about our different management impacts to get to our goal of species conservation.

A lot of this is already occurring on the landscape, so I would argue it's back to the basics with a lot of things that we can deal with existing stressors that humans have induced on the landscape over the last century. We're restoring flows and temperatures at the major hydroelectric dams. We're restoring connectivity like fish passage ladders or removing dams entirely, dealing with invasives when they get in stream networks.

In this study we showed that if you get on it early enough in the stages of invasion, you have a saving chance even with climate warming on the horizon. Maybe putting in barriers where you have populations that are threatened, maybe opening them where you don't. These are complex trade-offs that managers need to make in this uncertain future -- translocating species, thinking out of the box, looking at areas where you're going to put them at safeguards or refugia into the future, or areas where you're reintroducing them into formerly occupied habits. And finally, protecting, restoring, and reconnecting these critical habitats such as we've done with working with our partners in Canada to really fully understand how these relationships interact with healthy environments and how we can bring them back to provide healthy ecosystems and habitat conditions for fish populations and aquatic species to grow and survive and persist in this changing future.

I always leave a talk with "Give fish a chance." I think there's hope. I want to thank you all for attending this webinar today. I'd be happy to take any questions.

Ashley: We have one. It's from Donald. It says, "What are some of the management decisions that need to be considered, less commodities extraction?"

Clint: I think that management decisions have shifted. The paradigm's shifting. I think in the past it's been reactionary. In the case of native trout management, for example, managers are reacting to annual events like a collapsing stream bank and going out and repairing that at a very small scale.

I think in the context of climate change, managers are now thinking over broader landscapes and over longer periods of time and understanding that there's going to be winners and losers in the equation, and being able to anticipate the change and put the biggest bang for the buck where you're going to get it -- into the future.

I showed some examples of management activities that could bolster some fish populations into the future here. I think context matters. It depends a lot on what the current situation is in the system. For example, in the case of cutthroat trout, if a manager only has a few populations left that are genetically pure and they're at high risk of hybridization, a manager might have to put in a temporary barrier to protect the last remaining genetic strongholds for that species so then they can work on invasive species, habitat conditions, to try to re-found them to their historic habitats.

I think habitat management and protection of riparian zones is going to be very important into the future. Monitoring those habitats over time is going to be key because we have to evaluate change and how we're manipulating the environment to understand how species are responding and is adaptive management working?

Space and time and context matters. These are going to be difficult decisions in the face of uncertainty, but I think in a lot of cases it's back to the basics. Like I showed in my first couple slides, these fish have adapted to persist in a changing climate over thousands of years. More recently, they've declined dramatically to the point they're greatly depressed and the resiliency is greatly reduced. We have to build back that resiliency in areas where we can have hope.

I don't know if that answered that.

Ashley: We have another question from Donald, and it was just referring to "Could hybridization also be a survival strategy?"

Clint: I guess the verdict isn't out on that. It can be. Natural hybridization can lead to evolutionary novelty, adaptive radiation, and can actually create new species. From an evolutionary standpoint, natural hybridization is a key mechanism to promote persistence of different characteristics and even create new ones. It's a lot different than anthropogenic hybridization, human-mediated, where we've translocated fish in nearly every watershed in the United States. In some cases, there's been irreversible change.

I would argue that invasive species are the trump card for aquatic ecosystems. We can do everything to build back habitat, but hybridization is a one-way street. In the case of the cutthroat trout, that fitness slide that I showed, that's the first study that I'm aware of that has linked different levels of non-native genetic admixture with performance on the landscape. In this case, we looked at fitness in terms of reproductive success, and we related that to how hybridization may proceed or how it might increase in individuals. We found a strong negative effect there.

We found out-breeding depression occurring where anthropogenic hybridization is occurring in native trout. Over time, however, will those deleterious alleles or genes get purged and recombination take place and fitness will improve? The verdict's not out yet. I would argue though is that if you look across the entire range of all these cutthroat sub-species across the Western United States, hybridization, genetic in-aggression is by far the leading threat and has dramatically declined the genetic distribution of cutthroat.

In the case of westslope cutthroat, we only know of about less than 10 percent of their historic distribution. Now it contains non-hybridized populations. Again, those unique genes and gene complexes are linked to those adapted traits that allow these species to persist. Hybridization occurs -- it jumbles them up.

Ashley: And then a follow-up with that. “Has there been an effort to remove the invasive species in the hybridized zone to tip the balance back in favor of the cutthroat, despite conditions favoring the rainbows?”

Clint: That's a great question. There's only a couple examples in open connected stream systems -- one in Idaho and one in the Flathead. I've been a part of the one in the Flathead when we first discovered hybrids in the stream network. Montana Fish, Wildlife & Parks at the time, they have a dual mission -- providing recreational opportunities as well as protecting native species.

We found hybridization was increasing in this interconnected stream network. In the face of uncertainty, the managers went out, and we surgically implanted transmitters into the body cavities of these hybrids. They led us to the hybrid source population. It's like the Judas fish approach. We identified where these hybrid sources were on the landscape, and the managers, in the early stages of invasion, got on it and started suppressing and attempting to eradicate these sources.

Over time, over the last decade or so, we've seen a dramatic reduction in the number of hybrids at these sites, and we've seen a slowing of the spread of hybridization and a reduction in the percent genetic admixture in cutthroat populations that we've been monitoring in the system. In this case, it worked -- or it's working -- even with climate change because managers got on it in the early stages.

Ashley: “How does your work dovetail into or complement Dan Isaak's work with the US Forest Service?”

Clint: We've worked with Dan and his group on several projects. One good example of how our research programs are complementary is with Dan's temperature sensor network that he set up all over the Pacific Northwest, the NorWeST program.

That's been an amazing program, one, in my opinion, for people to gain an understanding of how climate change is affecting aquatic habitats over broad scales, and even at local scales. So for one, gaining a better understanding has been key, and then understanding that change by instituting and setting up a temperature sensor network across this broad landscape is very key for monitoring how warming impacts are occurring over these broad scales.

So that's been very important. We can link that to great models to predict occurrence and changes in species distributions, for example, into the future. That's going to be very key for management. An example of how our approaches with the daily models are complementary is that we can again look at different scales of fish performance, for example.

Not only these seasonal means and averages to look at changes over these scales, but we can actually link daily time step simulations with responses of fish populations, such as changes in growing days or emergence or the timing of spawning. I think that these different temperature modeling approaches are actually very complementary in a lot of cases.

Ashley: A couple more questions. One is from Elise and it says, "It's not uncommon to have one endangered fish species move into another endangered fish species' habitat where it previously did not occur. Do you have any thoughts about managing this?"

Clint: [laughs] Is that Alisa Wade?

Ashley: Kelley.

Clint: Oh, OK, I'm sorry. If an endangered species moved into another endangered species, so if there was a shift, how would we manage that? Is that the question?

Ashley: Yes, I think so.

Clint: Well, I'm not a manager. I'm a researcher. So what I would try to do is understand what's driving those interactions. I would say that if that's the case, that would be an area where you'd probably want to protect or conserve biodiversity, because we've got two species that are now asympatric, and if we're going to do adaptive management on the landscape, you're going to benefit two species.

If one species is negatively impacting one another, again, we're going to have to go back to "the context matters" and to understand the relative distributions and abundances and the genetic diversities of those species across the landscape. See where they overlap. See where maybe one species might have a broader range, the other doesn't, and try to develop approaches to hang-on to the one that's declining.

Again, I think my job is to provide data for managers. Those are difficult questions. I'm really not familiar with that happening on the landscape, although I could be wrong. That's a tough question. Those are difficult decisions. If anyone has examples, I'd love to hear about that.

Ashley: Another question from Janelle. It says, "Would you be able to address the Jarbidge River population in light of your climate change predictions?"

Clint: At the watershed metapopulation scale, yes. Right now, with the blue temperature and flow model, we can look at the vulnerability of those systems to change. We also have genetic data from the Jarbidge area. That was one of those populations that had low levels of genetic diversity. In the face of climate change in areas that are already on the southern limit of the range, such as that system, that might be an area where adaptation is going to be even more important. What we know now is that the genetic diversity is at its lowest there.

I don't know if that answers your question or not. I would say that the peripheral populations are important for evolution and climate warming. The more we can learn about how those species are under selection. Those selection pressures are greatest at those southern limits of the ranges. If we can learn more about the adaptive capacity and how certain regions of the genome are linked to temperature and flow, we can better understand how species elsewhere are going to respond. In the case of Jarbidge, we do have some data. Again, it's at the watershed scale. I would say that with Dan's temperature work coming online soon, linking that with VIC, you could probably get a better high resolution analysis of the impacts in the Jarbidge system. I would then add we've got abundance in genetic data. You could then look at how those might change into the future.

Ashley: Thank you. We're running low on time. We do have about four more questions. I'm going to take up two right now. "In your scaling up analysis, what do you think would change in your assessment if you considered other local characteristics, such as stream temperature, over air temperature, or flow gauged on that specific stream?"

Clint: I didn't catch the first part of that.

Ashley: "In your scaling up analysis, what do you think would change in your assessments if you considered other local characteristics?"

Clint: I guess the way I'd answer that is that at the smaller scale, we've found that the alluvial valley bottoms are going to provide critical areas for thermal refugia. Again, those are the areas with ground water, hyporheic flow. Those are the cold spots on the environment now and likely into the future. There's still a lot of things that we don't know about those areas.

What I would say is that scaling up, we'd want to be able to quantify where those areas occur, so we can build them as covariates into our models to better predict temperature responses. When you look at relationships of observed temperature to expected, there's a strong correlation there with our temperature models. The extremes, those outliers, tend to be those groundwater influenced areas.

I think if there's one area that we need to learn more about, and build that understanding into our modeling. It's understanding those groundwater influences and how those might change into the future. Nagle, with the Forest Service, developed an algorithm to predict that. I didn't show it in my slideshow, but using our daily stream temperature model and looking at a groundwater site, it predicted -- again, this is an algorithm we can apply to different landscapes -- that site actually showed up right in those alluvial valley bottom areas that were predicted by our model. We're trying to account for that in our stream temperature models.

For flow, I would say the biggest demand right now, or weaknesses, are that a lot of the flow gauge stations are in large rivers. We need to get a better understanding of what's going on at the local scale in smaller-order streams to get a better understanding of how flow influences fish populations, because truly, flow is a master variable.

Ashley: Thank you. Last question. It says, "I noted with interest your description of RCP 4.5 as a 'middle-of-the-road climate forecast.' In contract, our PCIC climate specialist described A2 and RCP 8.5 as 'roughly as business as usual,' B1 and RCP 4.5 as 'roughly half the emissions of business as usual,' and RCP 2.6 as 'aggressively optimistic greenhouse gas reduction scenarios.'" Do you care to comment?

Clint: Well, I'm not a climatologist, I'm a fisheries ecologist, for one. I can speak to that just in the case of our work, using RCP data. We compared RCP 4.5 to 8.5 predictions in the crown ecosystem, which I showed you at the beginning of our show, as well as the climate vulnerability work that Alisa has been working on. We haven't seen a lot of differences in changes in temperature and relative vulnerabilities across these different scales. But again, that's a broad statement from a naive scientist that relies on my climatologist to feed me those data to build into our biological assessments.

Ashley: Excellent. Thank you, Clint. And Shawn, did you have any closing remarks?

Shawn: I'm tempted to comment on that last question, but in the interest of time, I will say thank you very much, Clint. It was an excellent presentation.

Clint: Well, thank you all. It was a pleasure to be involved with the webinar series. I appreciate your time and attention. It's been fun, thanks.

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