Climanosco Research Articles

Collection 4, Oceans on the rise

# Will salmon disappear in warming world?

By Lisa Crozier, Dylan Gomes and Gordon Axel, 18 November 2024

RESEARCH ARTICLE

Wild salmon are disappearing from the world's oceans, but it is not entirely clear why or how we can stop it. Chinook salmon, also known as king salmon, is the largest species in the family Salmonidae. And yet, most populations in the contiguous United States are threatened with extinction. In addition to the many threats these fish face in their freshwater habitat, recent models have revealed that the ocean stage is at substantially higher risk due to climate change. Warming oceans may push numerous populations over the brink toward extinction. There are management strategies available, such as reducing contaminants with pervasive effects, reducing the number of hatchery fish that compete with wild salmon, and restoring habitat. We can save salmon, but we must work together to make the changes at the large scale that wild salmon need.

Wild salmon are disappearing from the world's oceans, but it is not entirely clear why or how we can stop it. Atlantic salmon from the eastern United States to northern Europe have nearly disappeared from the wild, and many southern races of Pacific salmon that use the high seas could soon face a similar fate. Chinook salmon, also known as king salmon, is among the largest species in the family Salmonidae. And yet, most populations in the contiguous United States are threatened with extinction. In addition to the numerous threats these fish face in their freshwater habitat from human influences, recent models [L.G. Crozier et al., 2021] have revealed that the ocean stage is at especially high risk due to climate change.

## How do we know this?

Cooperatively throughout the Columbia River Basin in the northwestern United States, biologists have tagged millions of fish since 1990 so they could be identified individually over their entire lifespan. For the populations studied here (figure 1), it starts by implanting very small transponders in these fish in their first summer, near where they were born. Teams of NOAA scientists and Army Corps engineers have built electronic devices into dams to detect these small tags even in huge spillways as fish travel downstream (as juveniles), and in fish ladders which adults use to move upstream (1-4 years later). We detect these tags many times, especially during migration, so we know the fish is still alive.

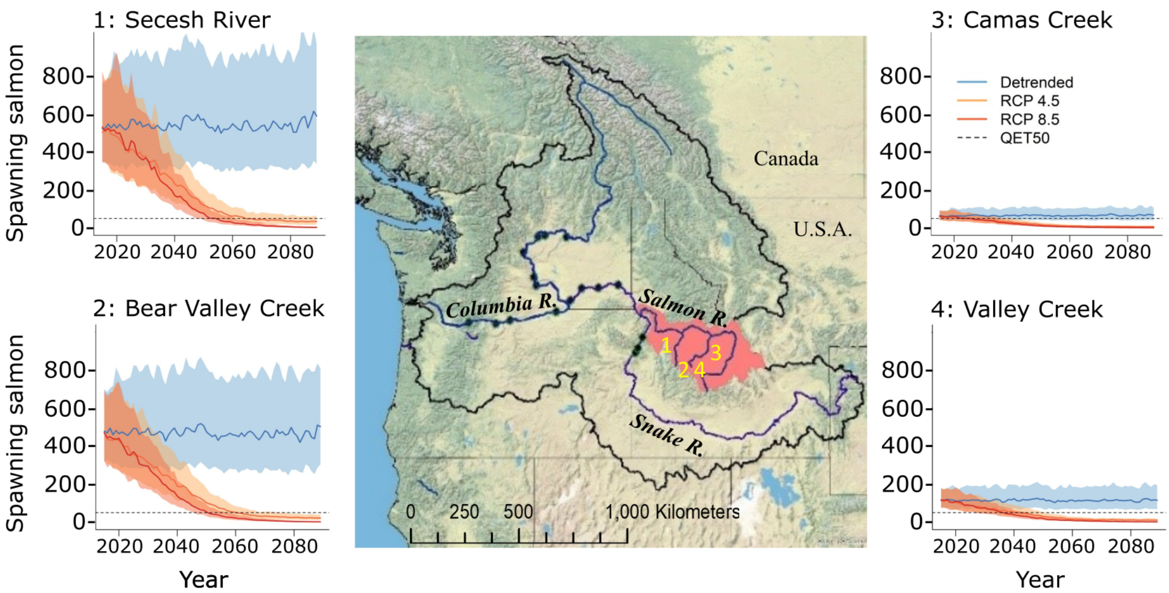


Figure 1. Map of the Columbia River Basin (black outline), with the Salmon River Basin highlighted in red. Model results for four of the populations are shown in the graphs, with locations indicated on the map as 1-4. The graphs show the change in population abundance over time. Solid lines show the median abundance while shading shows the interquartile range of population abundance across simulations for detrended (blue) vs. ensemble-mean global climate model projections for representative concentration pathways (RCP) 4.5 (orange) and 8.5 (red). Each population starts at its current abundance. A reference abundance of 50 spawners, the quasi extinction threshold (QET) is also shown (dashed horizontal line). Adapted from [L.G. Crozier et al., 2021].

This gargantuan effort allows scientists to build complex models of the entire salmon life cycle. These models include information about how many eggs a female of a given age can produce, how many of those eggs hatch, and then survive each year after that. This detailed information allows us to understand where in their life cycle salmon face the greatest threats.

Because we have collected these data over so many years, we can now include environmental variables in these models. Specifically, we are able to characterize how salmon respond to a wide range of environmental conditions in both freshwater and marine habitats. One such model was recently created for populations of wild Chinook salmon that included over 30 years of tag data, enough to characterize likely responses to climate change. These populations belong to the Snake River spring/summer Chinook salmon Evolutionarily Significant Unit, which the federal government listed as threatened under the U.S. Endangered Species Act in 1990. These populations have stabilized since they were protected, but now they face a new threat from climate change.

The fish in these populations migrate in the spring and early summer through the mighty Columbia River. Adults travel 1100-1400 km upstream, and climb up to 2000 m to reproduce in the same relatively pristine wilderness streams in the high mountains of Idaho where they were born. Then they die after spawning.

We have learned that in years with heavy fall rains, more juvenile fish survive until the following spring, where they can get a head start on the migration to the sea. Similarly, higher summer river flows increase the amount of habitat they can access during their prime growing season, helping them survive to the following spring. If they grow to a larger body size in freshwater, they are more likely to survive their perilous ocean stage.

With climate change, fall flows may not change very much on average, although rainfall could come in more intense storms. Fall flows may also increase. Summer flows, on the other hand, will likely reach new lows because of a decrease in summer precipitation, and increased evaporation due to warmer summer temperatures.

Survival during migration also relates to flows and temperatures. After winters with heavy snowfall, a large spring freshet of melted snow carries the juveniles swiftly along their long route to the ocean. The faster they travel in snow-cooled water, the more likely they are to survive the early ocean stage. With a changing climate, more of our winter precipitation will fall as rain rather than snow, causing the spring flows to become smaller and occur earlier in the year.

From the other direction, spring Chinook adults struggle in their migration upstream against raging flows, and they actually have an easier time of it when flows are reduced. Some of the populations included in this analysis migrate a little later than others, toward summer (known as summer Chinook), when stream temperatures start to track air temperatures more closely. Later-migrating fish are at higher risk of encountering stressful temperatures on both their juvenile and adult migrations. To avoid these temperatures, they start their migration earlier as they respond to cues in the environment.

Once salmon reach the sea, they are not free from the impacts of climate change. In the ocean there is a strong correlation between sea surface temperature and their survival. Less than 1% of spring/summer Chinook salmon return to streams as adults on average. After very warm ocean years, as we observed after the marine heatwave of 2014-2016, that number drops by half to a quarter. This is extremely concerning because sea surface temperatures are expected to rise 1-2°C by 2060, with much more frequent heat waves.

## Global climate expectations

Global climate models integrate complex physical dynamics to calculate how greenhouse gas emissions are altering the climate. Some models project faster warming than others, depending on how those models represent the relevant physics. Rates of warming also depend on how much carbon accumulates in the atmosphere. Carbon concentrations in 2100 are about twice as high in the Representative Concentration Pathway 8.5 vs 4.5, which are two possible future scenarios that we explored from the Coupled Model Intercomparison Project organized by the Intergovernmental Panel on Climate Change [R.K. Pachauri et al., 2014].

Part of the novelty of this analysis was our ability to measure the uncertainty in our results that came from differences in climate models. This ability stemmed from direct use of climate projections and the large number of these projections that are now available. Across the two carbon emissions scenarios, we examined 52 projections for ocean conditions and 20-80 projections from hydrological models for freshwater conditions.

A second important step was to link the freshwater and marine conditions in a given year, even though the projections came from different climate model runs. We used statistical methods to ensure that conditions faced by an individual fish tracked the transition from freshwater to the marine environment (and back) according to the appropriate migration timing, so that cumulative effects on an individual fish were correctly calculated.

## Simulating salmon populations

We then combined these climate projections with our life cycle models and added random variation in year-to-year weather to simulate possible futures. Within this simulated world, we were able to track the number of fish that were born each year and survive long enough to produce the next generation in eight populations. The size of each population over time is critically important. If a simulated population stayed very small (defined as 50 spawning adult salmon and known as a “quasi-extinction threshold”) for four years in a row, then that population is at a very high risk of extinction. This is because small populations are much more likely to go extinct than large populations. But even if populations do rebound from these low levels, there are genetic consequences for populations that pass through such “bottlenecks” in abundance. Genetic bottlenecks shrink the potential for future salmon populations to adapt to new environments.

Although populations randomly grow or shrink in any simulation, the average trend across all populations was stable – as long as we assumed there was no trend in climate (blue lines in graphs in figure 1). In the warming scenarios, however, we saw clear patterns in migration timing and survival. The shifts in timing helped them avoid some of the warming in the large rivers and improved ocean survival above what it would have been otherwise.

Nonetheless, when we imposed warmer sea surface temperatures on our modelled salmon, all populations declined (orange and red lines in graphs in figure 1). Even the largest populations eventually dropped below the dangerous quasi-extinction threshold. Dropping below this threshold does not mean that every population dies out. Some populations bounced back up after another year or two. So the model does not say that all Chinook salmon will be extinct in 50 years. It does say, however, that Snake River spring/summer Chinook salmon appear to be more vulnerable to climate change than most other threats, and we can no longer ignore this risk.

In trying to assess how confident we are in these projections, it is important to acknowledge that there are many unknowns when predicting how environmental conditions for fish will change in response to the full suite of impacts from global change. To be thorough, we did examine several possibilities. One possibility is that ocean productivity could go up. Off the shore of the western U.S., where these populations enter the ocean, winds typically pull surface waters offshore in the spring, which allows nutrient-rich deep water to rise to the surface. This upwelling process is a major reason that so many fish grow well in this region. Some climate models project that these winds will be stronger in the future, which might increase nutrients available for the entire ecosystem. Yet, the possible benefits for salmon will still have to overcome other negative effects of warming seas. In our model scenarios, increasing upwelling did help populations survive longer, but ultimately it did not prevent declines.

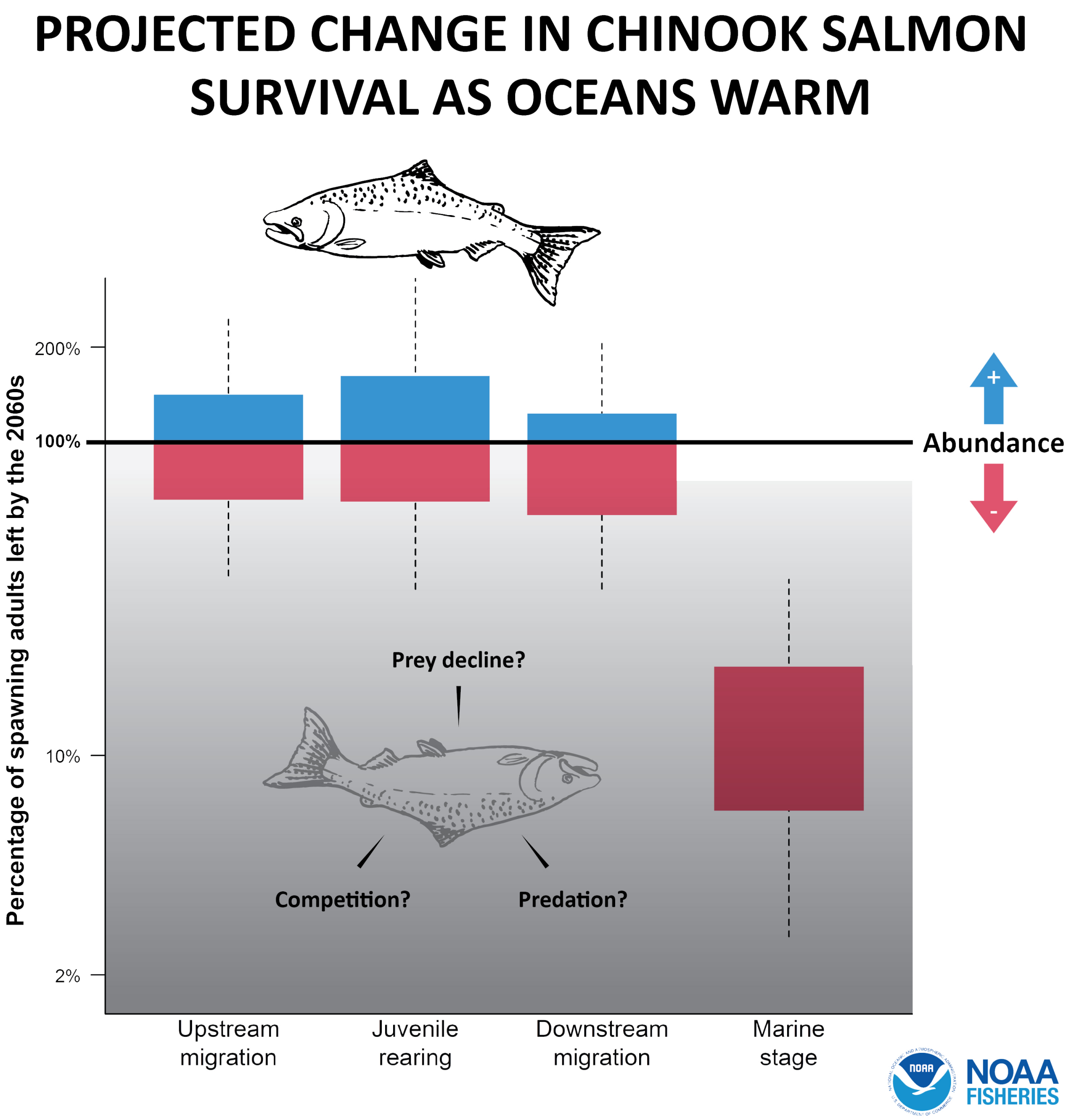


Figure 2. Change in population size across simulations for each scenario, in which climate change was imposed on only one life stage at a time. When climate change was only imposed in the three freshwater stages and not the ocean stage, populations sometimes increased (above 100%; shown in green) and sometimes decreased (below 100%; shown in red). However, when climate change was imposed in the ocean stage only, all populations declined. Boxes show the 25%-75% range of simulation results within a scenario, with the full range of results shown with the dotted line.

## Summarizing thoughts

After tagging millions of Chinook salmon and tracking them through major hydropower projects in the Columbia and Snake rivers, we can use life cycle modelling to understand how a changing climate might affect salmon populations. These models demonstrate that survival in the ocean stage is the most vulnerable part of the life cycle (ocean survival declined by

80-90% by the 2060s, figure 2). However, the ocean stage is the part that we know the least about.

Our knowledge gap partly reflects the physical challenge of studying the ocean. But even more importantly, it is because salmon interact with so many other species during this life stage. What makes this endeavor more challenging is that ocean ecosystems could change into a new state that is unlike any state we have seen in the past – that is, we might see an “ecological surprise.” Many of these possible ecosystems are likely to be less favorable for salmon than the ones we have modeled. For example, ocean acidification could have ecological or physiological effects on Chinook salmon that reduce their survival or ability to navigate their way home. Furthermore, other species, like jellyfish, are expected to increase in a warming ocean and compete with salmon for food.

On the optimistic side, it is possible that some future changes could help salmon to avoid extinction. Many species will change their distributions, and some of them might provide new food sources for salmon. One other option is that warming might occur slower than the average projections we have shown. What actually happens will be like a single simulation, which could go in any direction in the short term. Perhaps simple slowing of further declines will allow us time to improve our understanding of the factors affecting ocean survival, and implement more actions to help them persist. Therefore, it is very important that we do not give up on protecting these threatened species.

## Management actions

People have many impacts on the ocean. We usually think of fishing as our primary influence, and we certainly do fish many of the species that salmon eat. Salmon eat krill and the early life stages of crabs and fish of many types, including rockfish, flatfish, herring, anchovy, and sand lance. Many of these species are fished only to support other fisheries as bait, but they could be better left in the ocean. We also affect the habitat where these other species live and reproduce, such as in estuaries and along the coast. Perhaps we are having a greater impact than we currently realize. The plastics and other waste that we produce may be having more profound effects than we now know. We also release billions of hatchery salmon into the north Pacific every year. Hatchery salmon compete for limited feeding areas with wild salmon. Finally, the sharp rise in marine mammals since they were protected in the 1970s, such as seals, killer whales, and sea lions, has dramatically increased predation on salmon. Seals and sea lions often feed heavily on endangered salmon at choke points created by humans, such as at floating bridges and dams. These species have other prey choices and could alter their feeding areas.

We can also restore freshwater habitats where salmon spawn and grow. The model strongly indicates that far fewer juveniles can grow in freshwater compared with historical abundance, which lowers their resilience when ocean conditions are poor. The most productive freshwater habitat has been lost to human development, so the remaining habitats are at high elevation and low in nutrition. If we improve existing habitat or increase access to high-quality spawning and rearing habitat, they could produce more young salmon. We could also restore natural stream processes in lower elevations where young salmon grow better, which would improve the ocean survival of individuals, even if the number of juveniles does not increase.

We have learned a lot about how to restore salmon habitat effectively over the past 20 years. We are in a critical position right now where we could cooperate to complete the big projects that salmon need – such as restoring habitat that has already been developed, reconnecting stream channels, reallocating water to remain in streams or cool off underground to create thermal refuges, and removing invasive predators that we have introduced into salmon habitat. We can save salmon. But we have to work together to make these large changes that salmon need. We have no time to waste.

## Bibliography


- L.G. Crozier, B.J. Burke, B.E. Chasco, D.L. Widener and R.W. Zabel: Climate change threatens Chinook salmon throughout their life cycle, *Communications biology*, vol. 4(1), 1-14, https://doi.org/10.1038/s42003-021-01734-w, 2021.
- R.K. Pachauri, M.R. Allen, V.R. Barros, J. Broome, W. Cramer, R. Christ, J.A. Church, L. Clarke, Q. Dahe and co-authors: Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC, 2014.


### Article information

Cite as: Lisa Crozier, Dylan Gomes and Gordon Axel, Will salmon disappear in warming world?, *Climanosco Research Articles* **4**, 18 Nov 2024, https://doi.org/10.37207/CRA.4.1

ISSN 2673-1568
DOI https://doi.org/10.37207/CRA.4.1

Retrieved 1 Sep 2025
Version 1
In collection 4, Oceans on the rise

### Authors

Lisa Crozier, NOAA-Fisheries, Northwest Fisheries Science Center, Seattle, WA, USA
Dylan Gomes, contractor for Northwest Fisheries Science Center, Cooperative Institute for Marine Resources Studies, Oregon State University, Newport, OR, USA
Gordon Axel, Northwest Fisheries Science Center, NOAA-Fisheries, Pasco, WA, USA

## Categories

Climate of the future, Life, Ocean, Vulnerability, Pacific Ocean, USA

## Metadata

Date of final publication 18 November 2024
Type of article: Focus article; Single source article (L.G. Crozier, B.J. Burke, B.E. Chasco, D.L. Widener and R.W. Zabel, Climate change threatens Chinook salmon throughout their life cycle, Communications Biology, 4:222, 2021, https://doi.org/10.1038/s42003-021-01734-w)



Permanent url address:
https://www.climanosco.org/published_article/will-salmon-disappear-in-warming-world/