The Impact of Climate Change on the Migration Patterns of Fish Populations

Shangyun Li
Department of Mathematics and Statistics, Barnard College, Columbia University, 3009 Broadway, New York, NY 10027, U.S.A.

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Abstract: Climate change is reshaping marine ecosystems at an unprecedented rate, with significant increases in global temperatures leading to detrimental effects on the ocean's biophysical properties. This essay examines the profound impact of climate change on the migratory patterns of fish populations, as well as the cascading effects on marine biodiversity, human economies, and cultural practices. With a focus on the increased water temperatures, acidification, and sea-level rise caused by anthropogenic warming, the paper explores how these factors compel marine species to alter their traditional migratory routes, leading to ecological and evolutionary changes. The essay also discusses specific case studies, such as the response of salmon populations in Washington State, to illustrate the multifaceted nature of the crisis, and that these changes are far-reaching, affecting fishery yields, food security, and international relations. Finally, this paper assesses conservation strategies and policy changes necessary to mitigate these impacts, emphasizing ecosystem-based management, marine protected areas, and climate change mitigation efforts. The synthesis presented highlights the need for immediate and robust action to ensure the sustainability of marine life and human societies reliant upon it

1 INTRODUCTION

With global temperatures reportedly set to rise by 1.1 ℃, marine systems have become silent witnesses to the unspoken devastation of climate change. An alarming 60 percent of the world's marine ecosystems have already suffered degradation or unsustainable exploitation (Masson-Delmotte et al., 2018). The ocean, as the largest carbon sink on the planet, has absorbed about 90% of the excess heat from human-induced greenhouse gas emissions, culminating in a series of catastrophic events: melting ice caps, rising sea levels, intensified marine heatwaves, and progressing ocean acidification. This has set off a domino effect, impacting marine biodiversity and the global population reliant on these vital resources. Sea level rise has accelerated from 2013 to 2021, averaging 4.5 millimetres per year, and the incidence of ocean heat waves has doubled since the 1970s (Lee and Romero, 2023). With over half of the marine species projected to be at the brink of extinction by 2100 should the current temperature trends persist, the prognosis for marine and coastal ecosystems appears dire. A2 ℃ rise in temperatures is estimated to cause massive loss of coral reefs. The climate crisis is degrading the very migratory essence of marine life, with fish populations as the indicators of this aquatic upheaval.

2 OVERVIEW OF CLIMATE CHANGE

Climate Change, also referred to as “Global Warming” refers to the uptick in global temperatures as a result of increasing concentrations of greenhouse gas in Earth’s atmosphere (Shukla et al., 2022). Known as the greenhouse effect, greenhouse gases trap the Sun’s radiation and preserve the warmth of the planet. However, global industrialization on Earth has led to a steady spike in CO_2 concentrations, the main greenhouse gas. With the equilibrium of greenhouse gases in the atmosphere pushed higher and higher due to industrialization, clear global problems have been realized.

Since 1850, the earth's combined land and ocean temperature has steadily climbed at an average rate of

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0.11°F (0.06°C) per decade, cumulatively rising by approximately 2°F (Hayhoe et al., 2018). More concerning is the accelerated pace of warming observed since 1982, which has seen temperatures rising more than threefold, at 0.36°F (0.20°C) per decade (Masson-Delmotte et al., 2018). This uptick in temperature is catalyzing extreme weather phenomena worldwide, with heat waves setting new records both on land and in the oceans. Unprecedented rains, catastrophic floods, enduring droughts, rampant wildfires, and hurricane-induced floods are increasingly becoming the norm rather than the exception. Additionally, ice caps melting are increasing the acidification, sea level, and temperatures of the oceans. These evolving climate patterns portend greater challenges for our societies and natural environments, presenting complex issues that will only become more acute in the forthcoming decades.

For marine ecosystems in particular, the rapid changes in global weather and ocean conditions have led to increasingly apparent ecosystem-wide symptoms. Extreme weather events, such as the 2014 marine heatwave, have led to significant wildlife casualties (Pershing et al., 2018). During this event, many sea lion pups starved due to the relocation of their food sources, highlighting the devastating impacts that climate-driven changes can have on marine species and their habitats. Furthermore, changing temperatures is directly leading to changes in fish migration patterns. Projections indicate that by 2060, there could be declines of 20% to 30% in fish catches on America's East Coast due to the northward migration of fish species as waters warm. This shift in distribution poses challenges for the fishing industry and local economies dependent on these resources. As migration and food patterns of the oceans change, entire ecosystems are put in jeopardy.

3 EFFECTS OF CLIMATE CHANGE ON FISH MIGRATION

3.1 Fish Migration Patterns

3.1.1 Basic Principles of Fish Migration

Fish migrate to optimize survival and reproductive success, guided by environmental cues like photoperiod, temperature, and water levels (Nikola et al, 2022). These migrations are critical for finding suitable spawning grounds, securing food resources, and evading unfavourable conditions or predators. The study highlights that the lengthening of daylight hours is a universal cue prompting fish to migrate, with this signal being particularly influential on the timing and scale of these movements. In essence, fish are biologically programmed to respond to the subtle changes in daylight that herald the changing seasons, with each species having evolved specific patterns of movement that are synchronized with these natural rhythms.

3.1.2 Traditional Migration Patterns

Each fish species has historically followed distinct migration patterns, shaped by evolutionary pressures and ecological demands. Cyprinids, for example, commonly migrate in the spring, aligning their movements with the need for spawning habitats and food availability (Nikola et al, 2022). Salmonids, in contrast, undertake their upstream journeys mainly during summer and autumn, possibly due to different reproductive cycles and habitat preferences. These patterns represent a complex interplay between genetic predispositions and the species' adaptability to the riverine or lacustrine ecosystems they inhabit. The study emphasizes that while these traditional patterns are well-established, they are subject to alteration under the influence of environmental changes, particularly in artificial settings like reservoirs, which can significantly impact the migratory behaviors of both native and non-native fish populations.

3.2 Impact of Climate Change on Fish Migration and Marine Ecosystems

Environmental factors that trigger fish migration have been altered by climate change, leading to changes in phenology. Such changes in migration can have cascading impacts across the entire lifecycles of migratory fish-from the timing of spawning itself to the development of larvae and survival of juveniles-ultimately reverberating through the aquatic ecosystems they inhabit, and fish that typically migrate to spawn may now be undertaking these crucial movements earlier or later in the year as they respond to warming waters or changing seasonal patterns that are out of sync with evolutionary time (Tamario et al., 2019).

The disruption of the age-old migration patterns is a factor of the built-in evolutionary sensors fish have. Many ectothermic fish rely on living in waters that match their specific living temperatures. As water temperatures rise due to global warming, these

fish must search for cooler waters that remain within their optimal thermal ranges for growth, survival, and reproduction (Tamario et al., 2019). This behavioral shift often sees fish populations moving poleward or to greater depths, disrupting their traditional migratory routes and cycles in ways that can lead to mismatches between the timing of their journeys and the availability of suitable spawning grounds or food resources along the way.

For fish migrating between freshwater and marine environments, sea level rise and shifts in salinity gradients brought about by climate change present further challenges. As oceans swell, saltwater can intrude farther into coastal estuaries and river systems, reaching upstream areas used by migratory fish for spawning and nursery habitats. These altered salinity gradients can disrupt critical physiological processes in fish like osmoregulation, which balances salt and water levels internally (Hayhoe et al., 2018). The combined effects of habitat inundation and salinity changes may hinder the ability of diadromous species to successfully migrate, find suitable areas to spawn, and maintain robust populations. The impacts of climate change, however, go beyond just behavioral adaptations in migration timing and routes. As migratory fish face new selection pressures from altered temperature regimes, changing habitats, and other stressors, they may evolutionarily adapt through shifts in traits governing migration, survival strategies, and other vital characteristics. Over generations, fish populations may evolve to migrate at different times, follow new paths, or develop physiological adaptations to cope with rapidly changing environments. This can drive increasing genetic divergence, potentially leading to the emergence of new locally-adapted ecotypes or sub-species-reshaping fish communities and the structures of entire aquatic ecosystems, with cascading effects on biodiversity and ecosystem services.

In light of these multifaceted threats, understanding and addressing the impacts of climate change on migratory fish patterns is crucial for effective conservation and sustainable management of aquatic resources. As fish migrations shift in timing, routes, and species compositions, conservation strategies must also evolve to keep pace, taking an adaptive, forward-looking approach that accounts for both current conditions and projected future scenarios. This may necessitate establishing new protected areas, restoring critical habitats, and developing flexible management plans that can accommodate the changing migratory needs of fish populations over time. Moreover, prioritizing the maintenance of genetic diversity and the preservation of diverse migratory behaviors within and across species will be vital for bolstering the resilience of migratory fish in the face of ongoing climate change impacts. Only through such robust, climate-informed policies can we hope to sustain the ecological, economic, and cultural services provided by these iconic animal migrations in a rapidly warming world.

4 IMPLICATIONS FOR HUMAN SOCIETY AND SOLUTIONS

4.1 Direct Economic Impacts

Changes in fish migration patterns driven by climate change are having significant economic ramifications for the fishing industry and seafood supply chains. As fish populations shift distributions to stay within their preferred temperature ranges or follow shifting food sources, they may abandon traditional fishing grounds. This can lead to reduced catch and diminishing yields for local fisheries in areas where the fish exodus, directly impacting the livelihoods and incomes of fishers and fishing communities that have historically relied on those stocks (Washington Department of Fish and Wildlife, 2021). The downstream effects ripple through local economies as well, with decreased fishing revenues translating to reduced economic activity and job losses in industries supported by commercial fishing. Simultaneously, as fish stocks migrate to new regions, they can disrupt established seafood supply chains by creating product availability shortages in the areas they depart and surplus gluts in the regions they arrive. This volatility can lead to price fluctuations that make seafood less accessible to consumers, while processors, distributors, and retailers struggle to adapt sourcing, logistics, and sales to the shifting geographic distributions of catch.

The fishing industry itself also faces immense adaptation costs as key stocks relocate or alter their movements. Fishers may need to invest in new gear and vessels capable of accessing fish that have moved into deeper waters or completely different regions (Washington Department of Fish and Wildlife, 2021). Longer voyages to reach emerging grounds drive up fuel expenditures as well. There are also potential regulatory hurdles to adapt to as catch boundaries and seasons may need to be renegotiated with new migrations crossing jurisdictional borders. Making these capital-intensive operational changes can be particularly challenging for small-scale fisheries that

often lack resources and struggle to raise funds for retrofitting their practices. Ultimately, the downstream impacts on seafood prices, product availability, market economies, and human employment are highlighted. Policies and industry behaviors in the fisheries industry need to change in response to changing climate realities, or else changes in fish migration could be extremely disruptive.

4.2 Indirect Economic Impacts

Beyond just economic disruptions, shifts in fish migration patterns catalyzed by climate change could have severe ripple effects on food security, employment, international relations, market dynamics, and cultural heritage across the globe. In many developing regions, fish represent a vital source of protein and essential nutrients for billions of people. Drastic changes or declines in local fish stocks due to species redistributions could threaten food security and public health by increasing the risks of malnutrition and associated ailments (Washington Department of Fish and Wildlife, 2021). The socioeconomic toll would be further compounded by potential mass job losses in fishing, processing, and allied sectors that entire coastal communities depend on. This could necessitate extremely challenging economic diversification away from fishing livelihoods that have persisted for generations.

On a geopolitical scale, fish migrations into new waters could spark international disputes over fishing rights, regulations, and enforcement as fish distributions Start to straddle maritime boundaries. This could strain international relations and trade dynamics, with some nations needing to import fish they previously could source domestically. The global seafood market itself may experience major disruptions and realignments as the abundance and availability of high-value species shift to different regions, upending established supply chains (Washington Department of Fish and Wildlife, 2021). Countries that historically dominated as major exporters could lose substantial market share to emerging producers better situated to access relocated fish populations.

Perhaps most profoundly, climate-driven fish redistributions represent an existential threat to the cultural identities and practices of coastal communities that have been deeply intertwined with local marine species for centuries or millennia. As functionally irreplaceable fish depart, it could lead to the irreversible decay of cultural traditions, folk knowledge, and spiritual connections that represent an invaluable intangible heritage. The vast global ripple effects underscore how disruptive and destabilizing marina species migrations could become across humanitarian, economic, political, and social dimensions without concerted mitigation and adaptation efforts.

4.3 Conservation Efforts

Given the multitude of threats posed by climate change to marine environments and fisheries, a diverse array of management tools and conservation efforts are being leveraged in an attempt to bolster ecological resilience. There has been an increasing shift towards ecosystem-based management (EBM) approaches that consider the entire ecosystem, including human communities when devising strategies to maintain marine areas in a healthy, productive, and resilient state (Lam et al., 2016). A centrepiece of many EBM plans is the establishment and expansion of marine protected areas (MPAs) aimed at conserving biodiversity hotspots, sheltering critical habitats, and ensuring sustainable fish stocks-with some MPAs designed specifically to protect areas that could serve as climate refugees.

More traditional regulatory measures like catch quotas, size limits, and seasonal closures remain vital for preventing overfishing of vulnerable species and allowing depleted populations to recover (Lam et al., 2016). Habitat restoration projects focused on rebuilding areas like coral reefs, mangroves, and seagrass beds that provide essential nursery habitats during key fish life stages are also underway in many regions. As the impacts of climate change intensify, fishery managers are beginning to incorporate environmental data into adaptive stock assessments and management plans to improve the sustainability of wild-capture fisheries.

These on-the-ground initiatives are supported by significant investments into scientific research and monitoring programs aimed at better understanding the dynamic effects of climate change. This includes tracking changes in fish distributions, abundances, productivity, and other indicators across species to guide management interventions. Complementary efforts are also being made to reduce other compounding stressors like pollution, habitat destruction, and invasive species that can further undermine the resilience of ecosystems facing climate impacts.

On a global governance scale, international frameworks like the United Nations Convention on the Law of the Sea and the Sustainable Development Goals are guiding comprehensive, cooperative approaches to marine conservation and sustainable

use of ocean resources in the era of climate change. Country-level progress is being made as well by engaging local communities in sustainable fishing practices, developing alternative livelihoods to reduce extractive pressures, and implementing robust climate mitigation policies to reduce greenhouse gas emissions causing arctic warming and ocean acidification.

While pitched as an all-hands-on-deck effort utilizing every available tool, the success of these disparate management approaches and conservation initiatives in stemming climate change's toll on marine ecosystems and fisheries remains uncertain. What is clear is that failing to take comprehensive action could have catastrophic and irreversible consequences for the biodiversity, food security, and socioeconomic stability of coastal nations around the globe.

5 CASE STUDY-THE IMPACT OF CLIMATE CHANGE ON SALMON POPULATIONS IN WASHINGTON STATE

Salmon species in Washington State are confronting a severe environmental crisis that has been greatly exacerbated by the impacts of climate change. Over just the past six decades, average annual air temperatures in the state have risen by 1.77°F from 1960 to 2020 (Adriaan et al., 2009). This may seem like a relatively small increase, but it is already having profound ripple effects across the ecosystems that salmon depend on for their survival. With atmospheric CO_2 levels continuing to rise, climate models project this warming trend will likely accelerate in the coming decades, putting further strain on salmon habitats and life cycles.

One of the most visible manifestations of this warming has been the rapid melting of glaciers across the Pacific Northwest region. Glaciers act as frozen reservoirs that are critically important for replenishing streams with cold meltwater during the summer months when juvenile salmon are going through key developmental stages. However, as temperatures rise, these glaciers are disappearing at an alarming rate. Compounding this loss, mountain snowpacks that typically build up over the winter months and provide an additional source of runoff in the spring and summer are also diminishing as more precipitation falls as rain instead of snow due to the increases in freezing levels.

The data reflects the severity of this problem-from 1955 to 2016, there was a 21% decrease in the amount of water released from snowmelt across the western United States (Adriaan et al., 2009). With lower spring/summer stream flows, river temperatures are becoming perilously warm for the cold-water-adapted salmon. Readings frequently exceed 64℉, high enough to cause severe thermal stress. If temperatures surpass 70℉, the conditions can turn lethally warm, especially for more sensitive species and life stages like eggs and juvenile fish.

The warmer, lower flows are also exacerbated by increased water demands to support agriculture through irrigated crops and urban population centers. This creates a compounding effect as river water is diverted away from natural habitats, further reducing flows during the summer months when salmon need it most. Development of floodplains and marine environments have also degraded and eliminated some key rearing habitats while limiting the natural ability of river systems to temporarily store and slowly release floodwaters during high flow periods.

Beyond just creating stressful low-flow conditions, the shifts in the timing and volume of water moving through these systems disrupt the synchronized life cycles that salmon have evolved over millennia. More frequent and intense flooding can scour away gravel beds where salmon lay their eggs (redds). It can also displace juvenile fish prematurely into saltwater environments before they have been able to prepare physiologically, leading to high mortality. At the same time, unusually low water levels can strand fish in side channels and residual pools, cutting off their migration corridors.

Looking ahead, climate models suggest the situation will continue to deteriorate for salmon. Projections for Washington indicate spring snowpack levels may plummet by 56-70% by the 2080s compared to late 20th-century baselines. This would translate to even lower summer flows, higher water temperatures, and increasingly inhospitable conditions for salmon at key life stages in freshwater habitats.

Additionally, rising ocean surface temperatures have led to nutrient-poor, low-oxygen water conditions in areas like the coastal zones off Washington where juvenile salmon go to feed and mature. These degraded marine conditions favor subtropical zooplankton species that provide inadequate nutrition for growing salmon compared to their typical diet in a healthy ocean ecosystem.

Although salmon is a remarkably resilient species that has adapted to vast environmental changes across their evolutionary history spanning thousands of

years, the pace and multitude of impacts caused by modern climate change are testing the limits of their adaptive capacity. With habitats degrading quickly due to warming waters, loss of glacier and snowpack reserves, ocean acidification, and other climactic stressors, the genetic diversity and phenotypic plasticity of salmon populations are being outpaced. This has put the future viability of many distinct salmon runs and species at high risk in Washington State.

To confront this looming crisis, an aggressive multi-pronged strategy focused on both mitigating climate change drivers and adapting habitats will be required to sustain and recover these iconic salmon populations. Vital conservation measures include legal protections to preserve remaining high-quality habitats, restoration of degraded ecosystems like river floodplains, and strategic water management to ensure adequate flows during summer months. However, these efforts will be fighting an uphill battle against climate change without concerted global action to reduce carbon emissions and curb further atmospheric warming and ocean acidification.

Continued robust scientific monitoring and research will be essential for understanding the rapidly evolving impacts and developing potential interventions. However, lasting solutions will ultimately depend on legislative actions centered on environmental policy reforms and promoting renewable energy transitions to reduce greenhouse gas pollution. Community engagement and behavioral changes by individuals, corporations, and governments alike will also be imperative for driving the collective action needed to create a resilient environment in which critically endangered salmon populations can recover and thrive. The future of these fish hangs in the balance, with their persistence or extinction hinging on society's willingness to confront the climate change crisis head-on through aggressive mitigation and adaptation strategies in the decades ahead.

6 CONCLUSION

In conclusion, climate change is disrupting fish migration patterns around the world in profound ways, with far-reaching ecological, economic, social and cultural consequences. As waters warm, many fish species are being forced to abandon their traditional grounds and timing in search of suitable temperature ranges, upending cycles and movements calibrated by evolution over millennia. This breakdown in synchronicity between environmental cues and migration is derailing the organized progression of critical life stages like spawning and juvenile development. The impacts ripple across entire aquatic ecosystems as the redistributions of key species reshuffle food webs and nutrient flows in ways that can diminish overall productivity and biodiversity. For human communities, these shifts translate to reduced yields in long-established fisheries, supply chain disruptions, job losses, risks to food security, and the potential erosion of cultural identities deeply intertwined with marine species. On a geopolitical scale, disputes may emerge overfishing rights as stocks migrate across maritime boundaries. Tackling such a complex crisis requires an equally multifaceted response drawing from the full arsenal of conservation and management tools. This includes embracing ecosystem-based approaches that holistically account for human and ecological needs, establishing climate-resilient protected areas, dynamically adjusting fishing regulations and quotas based on the best available science, investing in habitat restoration, and internationally cooperating on sustainable resource use. At the same time, the root causes of climate change must be confronted head-on through aggressive efforts to transition global energy systems away from greenhouse gas emissions and toward renewable sources to curb further warming and ocean changes. Like so many other environmental issues, the impacts on fish migrations exemplify how climate change is an all-encompassing threat multiplier that cannot be solved through isolated, reactionary policies. Only a paradigm shift in how humanity treats the planet can safeguard the future viability of precious natural phenomena like cyclical animal migrations that have occurred long before human civilization emerged. Preserving these iconic movements that are intertwined with the delicate balance of marine ecosystems and the cultural fabric of coastal societies must be prioritized. While complex, solutions rooted in science and responsive governance are possible if the political will and public support can be mustered. The consequences of complacency, however, could be as profound as the unravelling of a fundamental biological tapestry eons in the making. Sustaining fish migrations is not just about ensuring stable food sources or economic revenues, but about maintaining humanity's humble connection to the enduring rhythms of life on this planet we all call home.

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