CHAPTER 9

Interactive Effects Of Climate Change And Environmental Toxicants On Fish Physiology And Health

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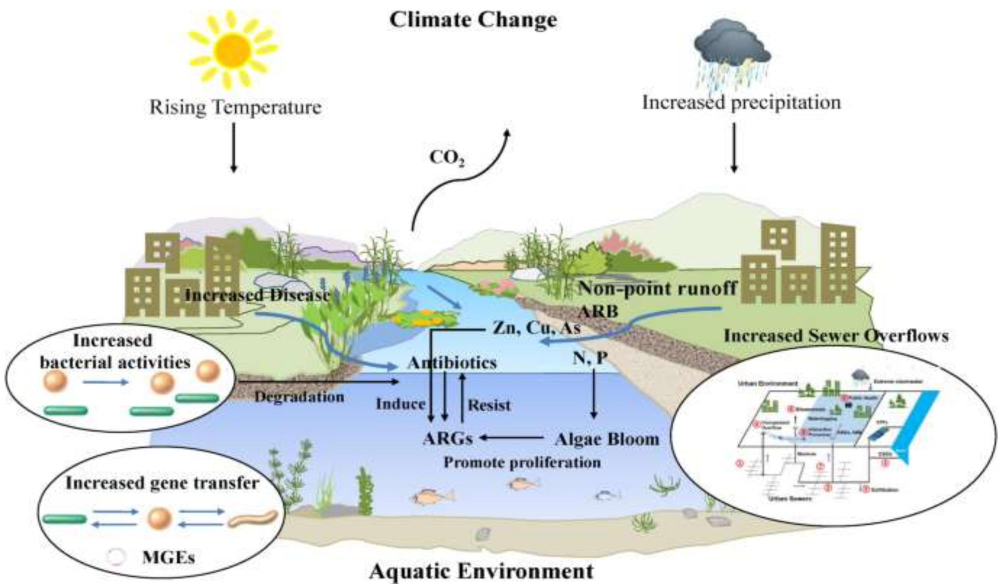
DOI- https://doi.org/10.59436/B978-81-971444-7-9/9

Climate change and chemical pollution are two significant human-driven factors that are reshaping our aquatic ecosystems today. The way they interact creates challenges that fish face regarding their health and physiology like never before. As global temperatures rise, we're seeing shifts in crucial environmental factors such as water temperature, oxygen levels, pH, salinity, and water cycles. Since fish are ectothermic, their growth, metabolism, reproduction, and overall survival are closely linked to these changing conditions. Even slight changes driven by climate can greatly affect how vulnerable fish are to other stressors, especially harmful pollutants. Aquatic environments are exposed to a variety of pollutants, such as heavy metals, pesticides, industrial chemicals, pharmaceuticals, and new contaminants that are emerging. In the past, toxicological studies have looked at how these substances affect ecosystems under fairly stable environmental conditions. However, there's increasing evidence that climate change can significantly alter the toxicity, bioavailability, uptake, and metabolism of these contaminants in fish. For instance, higher temperatures might boost chemical uptake and biotransformation, while conditions like low oxygen and acidification can hinder detoxification processes and change the nature of contaminants, resulting in increased toxicity. The way climate stressors and toxic substances interact can lead to effects that aren't just additive; they can actually amplify physiological stress in a synergistic way. These interactions can throw off energy metabolism, trigger oxidative stress, weaken immune responses, and disrupt both endocrine and reproductive functions in fish. Even sub-lethal impacts at the molecular, biochemical, and cellular levels can eventually ripple out to influence population dynamics, species distributions, and the overall stability of ecosystems. Understanding how climate change interacts with environmental toxins is crucial for accurately assessing ecological risks and managing our aquatic resources effectively. As climate change continues to unfold, fish are facing more extreme and variable environmental conditions, which could amplify the effects of pollutants beyond what current regulations account for. This chapter delves into the ways climate change alters the toxicological responses in fish, focusing on their physiological health and the importance of adopting integrated, multi-stressor strategies in aquatic ecotoxicology.

Climate Change Stressors Affecting Aquatic Environments

Climate change is having a significant impact on our aquatic environments, introducing a range of stressors that disrupt the physical, chemical, and biological balance of both freshwater and marine ecosystems. As global temperatures rise, water temperatures are also increasing, which directly affects the metabolic rates, growth, reproduction, and survival of aquatic life. When thermal stress surpasses what species can tolerate, we see shifts in where species are found, changes in community structures, and a higher risk of diseases (Pörtner & Farrell, 2008). Changes in precipitation patterns and the rising frequency of extreme weather events are ramping up hydrological variability, leading to floods, droughts, and shifts in river flows. These alterations disrupt the availability of habitats, sediment transport, and nutrient cycling, especially in river and wetland ecosystems (IPCC, 2022). In coastal and marine environments, the rise in sea levels results in habitat loss for estuaries, mangroves, and coral reefs, while increased water column stratification hampers oxygen mixing. Ocean acidification is a serious issue caused by the increased absorption of carbon dioxide from the atmosphere. This process lowers the pH levels in our oceans and reduces the availability of carbonate ions, which are crucial for organisms like corals, mollusks, and certain types of plankton to build their shells and skeletons (Doney *et al.*, 2009). On top of that, climate change leads to hypoxia, which is often made worse by nutrient pollution, creating low-oxygen areas that make it tough for fish and invertebrates to thrive. The combined and interactive effects of these factors can significantly impact the environment, weakening the resilience of ecosystems and jeopardizing vital services like fishery productivity, water quality management, and the preservation of biodiversity. To create effective management and conservation strategies in our ever-changing climate, it's crucial to grasp these interconnected stressors.

Environmental Toxicants in a Changing Climate



Aquatic ecosystems are facing an increasing threat from a variety of environmental toxicants, such as heavy metals, pesticides, industrial chemicals, pharmaceuticals, and new contaminants like microplastics. Climate change plays a significant role in how these substances behave, move, and affect fish health. As water temperatures rise, chemical reactions speed up and fish metabolism increases, which can lead to greater absorption of contaminants, their transformation, and accumulation in their bodies (Noyes *et al.*, 2009). Often, the changes driven by temperature result in metabolites that are even more toxic than the original compounds. Changes in precipitation patterns and the rising number of extreme weather events, like floods and droughts, have a significant impact on how contaminants behave. Flooding can lead to more runoff from farms and cities, which means higher levels of pesticides and nutrients entering our water systems. On the flip side, droughts can cause pollutants to become more concentrated in smaller amounts of water (Schiedek *et al.*, 2007). Moreover, climate-related shifts in pH, especially ocean acidification, can alter the chemical forms and availability of metals, often making them more toxic to fish and other aquatic life (Pörtner & Farrell, 2008). When hypoxia is intensified by warming and nutrient pollution, it can disrupt the detoxification processes in fish, making it harder for them to metabolize and eliminate toxins. These climate-driven changes collectively heighten toxic stress, underscoring the importance of integrating climate considerations into ecotoxicological risk assessments and developing adaptive management strategies.

Interactive Effects on Fish Physiology

a. Metabolic and Energetic Disruption

When fish are exposed to higher temperatures along with environmental pollutants, they face some serious metabolic and energy challenges. As the climate warms, fish experience an increase in their metabolic rates, which means they need more oxygen and expend more energy just to stay alive. This situation forces a larger chunk of their available energy to go towards maintenance and detoxifying their bodies, leaving them with less energy for growth, reproduction, and keeping their immune systems strong (Pörtner & Farrell, 2008). Plus, higher temperatures can boost the absorption, transformation, and accumulation of harmful substances, which adds to their physiological stress (Noyes *et al.*, 2009). All these factors can reduce their overall fitness and might even threaten their long-term survival.

b. Oxidative Stress and Cellular Damage

Climate change brings about various stressors like thermal stress, hypoxia, and acidification, which can lead to an increase in reactive oxygen species (ROS) in fish tissues. Additionally, many toxic substances, including metals and organic pollutants, can further boost ROS production. When these stressors hit at the same time, the fish's antioxidant defense systems—like superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx)—might struggle to keep up, resulting in oxidative damage (Lushchak, 2011). An overload of ROS can lead to lipid peroxidation, protein oxidation, and DNA damage, which can disrupt cellular function and make fish more vulnerable to diseases (Schiedek *et al.*, 2007).

c. Endocrine Disruption

Many pollutants found in water act as endocrine-disrupting chemicals (EDCs), messing with the hormonal regulation in fish. Climate change can worsen this issue by altering temperature and pH, which in turn affects hormone metabolism and the availability of EDCs (Kidd *et al.*, 2007). Disruptions in hormones related to thyroid function, stress (cortisol), growth, and reproduction can negatively impact development, stress responses, and reproductive success, potentially leading to broader effects on fish populations.

d. Neurotoxicity and Behavioral Alterations

The neurotoxic effects of pesticides and metals can get worse when climate stress is involved. Higher temperatures may boost the uptake of these neurotoxic substances and change how neurotransmission works. This can lead to problems like impaired swimming ability, altered predator avoidance, decreased feeding efficiency, and disrupted migration patterns (Scott & Sloman, 2004). These changes in behavior can have a direct impact on survival and ecological interactions.

Effects on Fish Health and Immune Function

- **Immunosuppression**

  Climate change is creating serious environmental stress for fish, especially with rising temperatures, low oxygen levels, and changes in water chemistry. These factors can really compromise their immune systems. When their bodies struggle to maintain balance, cortisol levels rise, which can suppress their immune responses. On top of that, environmental pollutants like pesticides, heavy metals, and industrial waste can further weaken their immune function by reducing their ability to fight off infections, produce antibodies, and communicate through cytokines (Reid *et al.*, 2019). When fish are hit with both climate stress and toxic exposure at the same time, the results can be even more severe, leading to a greater risk of disease and more frequent pathogen outbreaks in both wild and farmed fish populations (Marcogliese & Pietrock, 2011).

- **Histopathological Alterations**

  The combined impact of climate stressors and toxic substances often results in significant histopathological damage to vital organs. Gills are particularly at risk because they are in direct contact with the aquatic environment and play a crucial role in processes like respiration, osmoregulation, and excretion. Common structural changes seen under combined stress exposure include lamellar fusion, epithelial lifting, and necrosis (Schiedek *et al.*, 2007). The liver and kidneys, which are key players in detoxification and waste removal, frequently show signs of cellular degeneration, vacuolization, and inflammation. Additionally, damage to gonadal tissue can negatively affect reproductive capabilities.

- **Reproductive and Developmental Toxicity**

  When fish are exposed to elevated temperatures and contaminants, it can really mess with their reproductive health and the early stages of their lives. There's a lot of evidence showing that this can disrupt things like gametogenesis, hormone regulation, embryonic development, and how well larvae survive, especially when they come into contact with endocrine-disrupting chemicals (EDCs) (Kidd *et al.*, 2007). These impacts can change how sex is determined and lower the chances of successful recruitment, which can ultimately lead to declines in fish populations and weaken the resilience of ecosystems.

Ecological and Population-Level Consequences

Climate change and environmental pollutants don't just affect fish on an individual level; they also have a ripple effect on ecosystems and fish populations as a whole. When fish are under chronic stress, it can lead to stunted growth, lower reproductive success, and even higher mortality rates. This can result in fewer fish overall and changes in the age structure of the population (Pörtner & Peck, 2010). If recruitment is impaired due to issues like reduced egg viability and larval survival, it can really hamper a population's ability to recover. Moreover, as climate change alters how toxic certain contaminants are, we might see shifts in species distributions, with more tolerant species thriving while those that are sensitive decline. This shift can lead to a loss of biodiversity and a change in community dynamics (Schiedek *et al.*, 2007). At the ecosystem level, shifts in fish behavior and population dynamics can disrupt the delicate balance of trophic interactions, energy transfer, and food-web stability. The decline of key fish stocks not only jeopardizes fisheries productivity but also threatens food security. These stressors can set off a chain reaction of ecological consequences, underscoring the importance of adopting integrated management strategies that address both climate change and chemical pollution to protect our aquatic environments.

Implications for Risk Assessment and Management

Traditional ecological risk assessments usually look at how environmental toxicants affect ecosystems in stable and controlled settings. But with climate change shaking things up—think rising temperatures, shifting pH levels, changes in oxygen availability, and salinity—these factors can really change how toxic contaminants are and how sensitive organisms are to them. This means that focusing on just one stressor might lead us to underestimate the ecological risks faced by fish populations (Noyes *et al.*, 2009). So, it's crucial to weave climate variables into our risk assessment frameworks to get a clearer picture of toxicological outcomes in the face of future environmental changes. When it comes to climate-informed risk assessment, we really need to embrace approaches that are tailored to specific life stages and consider the combined effects of various climate stressors and pollutants (Heugens *et al.*, 2001). From a management standpoint, adopting adaptive strategies like stricter limits on pollutant discharges, better watershed management, and habitat restoration can significantly boost ecosystem resilience. By merging climate projections with ecotoxicological data, we can make smarter decisions for conservation, fisheries management, and regulatory actions in our ever-changing aquatic environments.

Conclusion

Climate change and environmental pollutants are tough challenges that fish face, creating serious and increasing threats to their health and survival. Changes in temperature, oxygen levels, and water chemistry driven by climate change can make pollutants even more toxic, leading to issues like metabolic disruption, oxidative stress, hormonal imbalances, and weakened immune responses. These physiological challenges can reduce reproductive success, increase vulnerability to diseases, and alter survival rates, which in turn affects fish populations, their distribution, and the overall health of ecosystems. At a larger ecological level, the combination of stressors is really messing with food chains and putting a strain on fish productivity and the variety of life in our waters. Traditional methods that only look at one stressor just don't cut it when it comes to understanding these complex interactions. This makes it clear that we need integrated, climate-aware ecotoxicological frameworks. For future research and management, it's crucial to focus on assessing multiple stressors, conducting long-term monitoring, and adopting flexible strategies to lessen the combined effects of climate change and chemical pollution. This approach will help ensure that our aquatic ecosystems remain resilient and sustainable as the environment continues to evolve.

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