

CHAPTER 2

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Toxicological Stress In Fishes Due To Climate Changes

The global aquatic environment is undergoing unusual alterations primarily driven by modern climate change. While physical changes in oceans and freshwater ecosystems—such as rising temperature, altered precipitation patterns, and increased acidification—are widely recognized, a more subtle but equally significant threat emerges from the interaction between these physical shifts and chemical pollutants present in aquatic habitats. Fish, as ectothermic organisms, depend heavily on the thermal and chemical characteristics of their surrounding environment. Their physiological functions, metabolic activities, growth, and behaviour are strongly influenced by external environmental conditions, making them particularly susceptible to toxicological stress (Ficke, Myrick, & Hansen, 2007). Toxicological stress refers to the physiological strain imposed on organisms when environmental contaminants disrupt normal biological processes and compromise the organism's ability to maintain homeostasis (Sokolova & Lannig, 2008). Historically, environmental toxicology largely focused on the classical “dose–response” relationship, where the toxic effects of a particular chemical were

studied in relatively stable environmental conditions (Newman, 2015). However, contemporary environmental conditions are characterized by complex multi-stressor scenarios in which climate-related variables interact with chemical pollutants to amplify their effects. Climate change acts as a “force multiplier” by influencing the transport, transformation, and

biological uptake of contaminants in aquatic systems (Noyes *et al.*, 2009). Rising water temperatures, for example, can accelerate metabolic processes in fish, increasing respiratory activity and thereby enhancing the uptake of dissolved pollutants through the gills. Simultaneously, elevated temperatures can increase the solubility and bioavailability of certain toxic metals and organic chemicals, intensifying their toxic potential (Jeppesen *et al.*, 2014). Temperature-induced metabolic acceleration also increases the energetic demands of fish, forcing them to allocate more energy toward maintaining physiological balance rather than toward growth, reproduction, or immune defence. This energetic trade-off can weaken detoxification pathways and antioxidant defence systems, thereby exacerbating the harmful effects of pollutants such as heavy metals, pesticides, and industrial chemicals (Sokolova, 2013). For instance, metals like cadmium, lead, and mercury are known to disrupt enzymatic functions and induce oxidative stress in fish tissues, particularly in metabolically active organs such as the liver and gills (Authman, Zaki, Khallaf, & Abbas, 2015). When combined with elevated temperature or reduced oxygen availability, the toxicity of these contaminants can increase substantially. Another critical environmental factor influenced by climate change is the acidification of aquatic systems. Increasing atmospheric carbon dioxide concentrations lead to greater dissolution of CO₂ in water bodies, forming carbonic acid and subsequently lowering pH levels. Acidic conditions can alter the chemical speciation of metals and other pollutants, making them more biologically available and potentially more toxic to aquatic organisms (Doney *et al.*, 2012). Additionally, changes in salinity and dissolved oxygen levels—often associated with altered rainfall patterns, droughts, or eutrophication—further complicate the toxicological landscape experienced by aquatic fauna. Fish are particularly valuable as bioindicators of aquatic ecosystem health because they occupy various trophic levels and accumulate contaminants over time. Physiological parameters such as enzyme activity, oxidative stress markers, histopathological alterations, and behavioural changes are commonly used to evaluate toxicological impacts on fish populations (Van der Oost, Beyer, & Vermeulen, 2003). The study of such biomarkers has become increasingly important for understanding how combined environmental stressors influence the survival and resilience of aquatic organisms. As the world progresses further into the mid-21st century, the implications for global fisheries, aquatic biodiversity, and food security are profound. Fish constitute one of the most important sources of animal protein for billions of people worldwide and play a crucial role in maintaining ecological balance within aquatic ecosystems (FAO, 2022). Toxicological stress that results in impaired reproduction, developmental abnormalities, reduced growth, or large-scale mortality

events can therefore have significant ecological, economic, and social consequences. Declining fish populations not only threaten biodiversity but also jeopardize the livelihoods of communities that rely on fisheries and aquaculture.

Factors Affecting Aquatic Toxicity Due To Climate Change:

- **Rising Water Temperature**

Temperature is likely the most significant abiotic component in ichthyology. As water temperatures increase the kinetic energy of molecules escalates, so directly affecting the behaviour of chemical contaminants. For numerous fish species higher temperatures result in increased gill ventilation rates as the organism strives to satisfy increased metabolic oxygen requirements. This physiological change unintentionally increases the volume of water, so increasing the concentration of dissolved toxins passing the respiratory membranes. Moreover, heat can enhance the solubility of some compounds, hence increasing their bioavailability.

- **Ocean Acidification**

The absorption of atmospheric CO₂ by the oceans leads to a reduction in pH, a phenomenon referred to as ocean acidification. This change in chemistry modifies the speciation of metals. For instance, in more acidic aquatic environments, metals such as aluminium or copper may transition from less toxic particulate forms to highly toxic ionic forms Cu²⁺. For fish this implies that even if the overall concentration of a metal in the water remains unchanged, the "effective" toxicity is significantly increased as a result of the decrease in pH.

- **Altered Salinity and Hydrological Cycles**

Climate change alters the hydrological cycle resulting in excessive rainfall and flooding in certain regions while causing significant droughts in others. In coastal ecosystems, these variations induce swift alterations in salinity. Salinity affects the osmoregulation of fish, when a fish experiences stress due to salinity fluctuations its cellular pumps (such as Na⁺/K⁺-ATPase) operate at an increased rate. This metabolic strain affects the fish's ability to manage chemical stresses. Moreover, substantial precipitation can result in significant spikes of agricultural chemicals and urban runoff into water bodies causing severe hazardous incidents.

- **Hypoxia and Deoxygenation Events**

Increased water temperatures result in diminished dissolved oxygen levels creating "dead zones" or hypoxic environments. Hypoxia is a physiological stressor that compels fish to choose survival over growth or detoxification. In conditions of oxygen deficiency the liver's capacity to process poisons through cytochrome P450 enzymes is frequently impaired. The interplay of diminished oxygen levels and elevated toxicity frequently leads to synergistic lethality, when the combined effects are significantly more lethal than either cause independently.

Interaction Between Climate Change And Aquatic Pollutants

The interaction between climate variables and pollutants is categorized into two main frameworks: Climate-Induced Toxicant Sensitivity (CITS) and Toxicant-Induced Climate Susceptibility (TICS). In the CITS model, climate stressors such as elevated temperature can increase the sensitivity of fish to toxic substances (Noyes *et al.*, 2009; Sokolova, 2013). For example, a fish living near the upper limit of its thermal tolerance may lack the physiological "buffer" required to cope with additional chemical stress, meaning that exposure to contaminants such as mercury at concentrations normally considered sub-lethal may become harmful under warming conditions (Pörtner & Farrell, 2008; Ficke, Myrick, & Hansen, 2007). Conversely, in the TICS model, exposure to pollutants can impair physiological processes that enable fish to respond effectively to climate variability. Fish exposed to endocrine-disrupting chemicals (EDCs) may experience disruption of hormonal pathways involved in development and migration, potentially affecting processes such as smoltification and seasonal migration in response to changing environmental temperatures (Scholz & Mayer, 2008; Brown, Johansen, & Colgan, 2014). These interactions can be further intensified by the "pesticide treadmill" effect, where rising temperatures and shifting pest populations lead to increased pesticide usage in agriculture, resulting in greater chemical runoff into aquatic ecosystems during periods when fish are already physiologically stressed (Schäfer *et al.*, 2012; Noyes *et al.*, 2009).

Cellular Mechanisms Of Toxicological Stress

At the cellular level, the combination of climate change and toxins affects the mitochondria and the cell membrane.

- **Mitochondrial Dysfunction:** Heat stress can uncouple oxidative phosphorylation, while heavy metals can inhibit specific enzymes in the electron transport chain. Together they cause a collapse in cellular energy (ATP) production.

- **Protein Denaturation:** High temperatures cause proteins to unfold. Cells respond by producing Heat Shock Proteins (HSPs). However, many pollutants inhibit the synthesis of HSPs, leaving the cell's internal machinery unprotected from thermal damage.
- **Genotoxicity:** The combination of chemical mutagens and increased metabolic rates often leads to higher frequencies of DNA strand breaks and micronuclei formation, potentially leading to long-term genetic erosion in populations.

Effects On Growth, Reproduction And Survival

The energy budget of a fish is restricted. In a clean, stable environment energy is provided for growth and reproduction. Under toxicological stress caused by climate change energy is directed toward “maintenance” (detoxification, tissue repair, and enhanced respiration).

- **Growth:** Stressed fish often exhibit "stunting." Reduced growth rates make juvenile fish more susceptible to predation.
- **Reproduction:** Many pollutants are endocrine disruptors. When combined with temperature shifts (which often trigger spawning), the cues for reproduction become "mismatched." This can lead to reduced egg quality, lower sperm motility and complete recruitment failure.
- **Survival:** While acute mortality is easy to measure, "ecological death" where a fish is alive but too slow or weak to hunt or escape predators is a more common and equally devastating outcome of multi-stressor environments.

Ecological And Fisheries Implications

Toxicological stress impacts not only individual fish but also impacts within the food system. The alteration of a keystone species or primary consumer results in an overall shift in the community structure. We are observing a "tropicalization" of temperate seas, characterized by the forward migration of warmwater species. However, if these different environments become polluted with past contaminants (such as PCBs in sediments) the migratory fish encounter a new range of toxicological problems. This results in irregular yields for fisheries, diminished demand of fish caused by elevated pollutant levels (e.g., methylmercury) and the risk of collapse of crucial to culture local fisheries.

Mitigation, Adaptation And Management Strategies

To deal with this, we need to use many different methods:

a) Regulatory Reform: Moving away from "single-chemical" safety limits and toward "multi-stressor" risk assessments.

b) Habitat Restoration: Creating thermal refugia (areas of cool, deep water) and planting riparian buffers to filter chemical runoff.

c) Genetic Conservation: Identifying and protecting populations that show natural resilience to both heat and toxins for use in restocking programs.

d) Pollution Control: Reducing the primary load of nutrients and chemicals to give fish more "physiological room" to cope with unavoidable climate shifts.

Conclusion

The simultaneous study of climate change and aquatic toxicology creates one of the most complicated challenges in current environmental science. As discussed throughout this chapter, the stress experienced by fish is not just an additive effect of individual factors but an interrelated phenomenon in which physical environmental alterations significantly change the principles of chemical toxicity. The increasing temperatures, acidifying waters and variable oxygen levels of our future planet have transformed earlier acceptable pollution levels into deadly hazards. The evidence provided here highlights that fisheries management and water quality cannot be addressed independently; a comprehensive approach that encompasses climatology, chemistry and biology is essential. The ongoing survival of fish populations in the Anthropocene depends on our capacity to mitigate the chemical load imposed upon them. Although global climatic trends are challenging to alter in the short term, the local and regional release of pollutants is a factor within our direct control. By reducing pollution, we afford aquatic organisms the necessary "respiratory space" to acclimate to a warmer environment. The adaptability of our seas and rivers is finite; still, by effective management, thorough research, and a dedication to environmental preservation, we can ensure that fish and their supporting ecosystems continue to thrive amid the increasing stresses of climate change. The way forward requires the shift from reactive management to active safeguarding, ensuring that today's "toxicological stress" does not evolve become tomorrow's "extinction event".

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