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Review: The climate conundrum: Challenges and opportunities in aquaculture and fisheries

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Abstract
Climate change is profoundly affecting aquatic ecosystems, altering their physical, chemical, and biological components, which in turn threatens the biodiversity and stability of global fisheries. As both wild and farmed fisheries are integral to food security and the economy, particularly in developing regions, the effects of rising temperatures and environmental disruptions jeopardize essential protein sources for billions of people. The ongoing challenges emphasize the urgent need for effective strategies to mitigate climate impacts on aquatic environments and ensure sustainable fisheries management to safeguard global food security and economic stability in the face of climate change.

Keywords: Ecosystems, environmental, disruptions

1. Introduction
1.1 Global Impact of Climate Change on Aquatic Ecosystems
Climate change is a global challenge, disturbing balance of ecosystems and impacting biodiversity (IPCC, 2021) [27]. The rapid increase in global temperatures, contribute largely to anthropogenic greenhouse gas emissions, it has brought about various changes in environmental parameters, particularly in aquatic ecosystems. Oceans and freshwater bodies, acting as primary regulators of the earth's climate, are especially vulnerable due to their capacity to absorb excess heat and carbon dioxide (CO_2) (Hoegh-Guldberg *et al*., 2018) [2]. As temperatures continue to rise, these ecosystems are witnessing alterations in chemistry, biology, and physical structure, which directly affect aquatic organisms, including fish populations essential for global food security and biodiversity (Bindoff *et al*., 2019) [6].

1.2 Importance of Fisheries in Global Food Security and Economy
Fisheries, encompassing both wild capture and aquaculture, play a significant role in the livelihood of millions worldwide, contributing around 20% of the animal protein intake for over 3 billion people (FAO, 2022) [17]. Wild-capture fisheries provide an essential protein source, particularly in developing countries where alternative protein sources are limited. Simultaneously, aquaculture, the fastest-growing food production sector, now supplies nearly half of the global fish consumption, fulfilling the protein demands unmet by declining wild stocks (FAO, 2022) [17]. The global economic impact of fisheries extends beyond food provision; it encompasses employment, trade, and cultural practices, highlighting the need to understand and mitigate the effects of climate change on both wild and farmed fish stocks (Pauly & Zeller, 2016) [35].

1.3 Overview of Climate Change Impacts on Fisheries
Aquatic ecosystems are uniquely sensitive to climate change due to their reliance on temperature, pH, oxygen levels, and other environmental conditions. Climate change impacts, such as ocean acidification, rising sea levels, increasing temperature, and the expansion of hypoxic zones, create new challenges for the survival, limitations (Pörtner & Farrell, 2008) [38]. In contrast, aquaculture faces additional distribution, and reproduction of fish species (Doney *et al*., 2012) [13].

These changes influence species diversity, with certain species migrating to cooler regions or facing extinction due to physiological pressures, as fluctuating water temperatures and deteriorating water quality increase susceptibility to disease, alter growth rates, and impose significant economic burdens on fish farms (Froehlich *et al.*, 2018) [18]. Given the scope of these impacts, a comprehensive review is essential to inform sustainable practices and adaptive management strategies in both wild fisheries and aquaculture.

1.4 Objective and Scope of This Review

This review aims to provide a detailed examination of the impacts of climate change on wild fish stocks and farmed fish. The paper is organized to address how specific climate-induced changes—such as temperature rise, ocean acidification, and hypoxia—affect wild fish populations, with a subsequent focus on how these factors influence aquaculture. We will explore mitigation and adaptation strategies necessary to safeguard fisheries and discuss socio-economic implications for communities dependent on fisheries. The objective is to present an integrated perspective, drawing upon recent literature to establish a foundational understanding of the challenges and potential solutions for fisheries in the face of climate change.

2. Effects on Wild Fish Stocks

2.1 Temperature Rise and Species Distribution

As global temperatures increase, aquatic ecosystems experience significant shifts in species distribution, affecting both biodiversity and ecosystem stability. Many fish species are highly sensitive to water temperature, which regulates physiological processes, including metabolism, growth, and reproduction (Pörtner & Peck, 2010) [39]. Rising temperatures drive species to migrate toward cooler waters, often poleward or to deeper depths, disrupting established ecological niches and community structures (Cheung *et al.*, 2013) [10]. Studies have shown that warmer waters have led to a northward shift in the distribution of species such as Atlantic cod (*Gadus morhua*) and American lobster (*Homarus americanus*), impacting local fisheries that rely on these stocks (Kleisner *et al*., 2016) [29].

Temperature-induced distribution shifts also affect predator-prey dynamics. As species move to new regions, they interact with unfamiliar predators and prey, leading to competition and sometimes the collapse of local populations (Rutterford *et al*., 2015). These ecological changes challenge fishery management systems, which must adapt to the unpredictable movement of stocks essential for economic stability in fishing communities (Pecl *et al*., 2017).

2.2 Ocean Acidification

Ocean acidification, primarily caused by increased CO_2 absorption, poses significant challenges to marine life, particularly for species dependent on calcium carbonate, such as shellfish and corals (Doney *et al.*, 2009) [13]. Fish species experience altered behavior, sensory responses, and reduced survival rates in acidic environments, impairing their capacity to locate food, avoid predators, and successfully reproduce (Munday *et al*., 2009) [32]. The impact of ocean acidification on coral reefs is particularly concerning, as coral habitats support a large variety of marine species, providing food and shelter critical to their survival.

Species like the clownfish (*Amphiprioninae*) show significant disorientation in response to reduced pH levels, affecting their ability to navigate and recognize habitats, ultimately reducing survival and recruitment rates (Dixson *et al*., 2010) [12]. These behavioral and physiological responses in fish due to acidification emphasize the need for adaptive measures in marine conservation and management to support resilient fish populations in increasingly acidic waters (Nagelkerken & Connell, 2015) [33].

2.3 Hypoxia and Dead Zones

Increasing global temperatures and nutrient runoff from agricultural and industrial sources contribute to the expansion of hypoxic zones, areas with severely low oxygen levels detrimental to marine life (Breitburg *et al*., 2018) [8]. Hypoxia disrupts the aerobic metabolism of fish, leading to increased mortality, reduced growth rates, and altered feeding and reproductive behaviors (Vaquer-Sunyer & Duarte, 2008) [44]. In these "dead zones," fish are often forced to move to areas with higher oxygen levels, which may not have suitable habitats or food resources, leading to population declines and ecosystem instability.

For example, the Gulf of Mexico experiences one of the largest seasonal hypoxic zones, causing disruptions to commercially important species such as shrimp and bottom-dwelling fish. As hypoxia continues to increase in frequency and severity, managing nutrient pollution and promoting sustainable agricultural practices are essential to preserving the resilience of fish populations in affected areas.

2.4 Coral Bleaching and Habitat Loss

Coral bleaching, a direct result of rising sea temperatures, has severe implications for reef-associated fish species. As corals expel their symbiotic algae due to stress, they lose color and essential nutrients, often leading to large-scale coral death if conditions do not improve (Hughes *et al.*, 2018) [25]. Coral reefs are biodiversity hotspots, home to approximately 25% of all marine species, making their degradation a significant threat to global marine biodiversity.

Fish species reliant on coral reefs for food, shelter, and spawning sites, such as parrotfish (*Scaridae*) and damselfish (*Pomacentridae*), face habitat loss, leading to reduced population sizes and altered community structures. Moreover, coral bleaching diminishes the capacity of reefs to buffer coastal regions from wave action, contributing to coastal erosion and negatively affecting human populations reliant on these natural barriers (Ferrario *et al.*, 2014) [15]. Conservation efforts, including reef restoration and the establishment of marine protected areas, are essential to mitigating the impacts of coral loss on fish stocks and associated ecosystems.

2.5 Extreme Weather Events

The increased frequency and intensity of extreme weather events, such as hurricanes, storms, and floods, disrupt aquatic habitats, leading to physical damage, changes in salinity, and altered nutrient cycles. These events can result in fish displacement, habitat destruction, and increased mortality rates, particularly in shallow coastal regions where many juvenile fish reside (Walther *et al*., 2002) [45]. For instance, intense hurricanes can destroy seagrass beds and mangroves, which are critical nursery habitats for many commercial fish species, such as snapper (*Lutjanidae*) and grouper (*Serranidae*) (Alongi, 2008) [2].

Such habitat destruction compromises recruitment, with cascading effects on population dynamics and fishery yields. Moreover, storm-induced runoff from urban and agricultural areas introduces pollutants into marine environments, increasing stress on fish populations already struggling to adapt to changing conditions. Strategies to mitigate the impact of extreme weather on fisheries may include habitat restoration and sustainable coastal management practices to protect vulnerable ecosystems from further degradation.

3. Impact on Farmed Fish

3.1 Temperature Fluctuations and Growth Rates

In aquaculture, water temperature is a key factor influencing fish metabolism, growth, and reproductive cycles. As global temperatures rise, fish farms experience fluctuations that can lead to reduced growth rates or even mortality in temperature-sensitive species (Somero, 2010) [41]. For example, many commercially farmed species, including Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*), have optimal growth ranges between 12–18 °C, but elevated temperatures can exceed their tolerance thresholds, causing stress and reduced productivity (Handeland *et al*., 2008) [23].

Higher temperatures accelerate metabolic rates, increasing fish feed requirements and raising operational costs. Moreover, species-specific thermal tolerances limit the geographical distribution of aquaculture, potentially forcing farmers in warmer regions to switch to more heat-tolerant species, which may not yield the same economic returns. This need for adaptive strategies underscores the importance of selective breeding for heat-resistant species and exploring sustainable practices that enhance fish resilience to temperature stress.

3.2 Increased Disease Prevalence and Susceptibility

Climate-induced temperature shifts and water quality changes create conditions conducive to the spread of diseases and parasites in aquaculture. Warmer waters facilitate pathogen reproduction, increasing the risk of outbreaks that can devastate farmed fish populations. For instance, the proliferation of parasitic sea lice (*Lepeophtheirus salmonis*) has intensified with warmer temperatures, resulting in significant losses for salmon farms.

Bacterial diseases, such as vibriosis and streptococcosis, also flourish under elevated temperatures, posing severe threats to aquaculture worldwide. To combat these challenges, fish farms often rely on antibiotics and other chemical treatments, which contribute to antimicrobial resistance and pose health risks to consumers and surrounding ecosystems (Cabello, 2006). Disease management strategies, including the development of vaccines and improved biosecurity measures, are essential to mitigate these risks and sustain the profitability of aquaculture under climate-stressed conditions.

3.3 Water Quality Degradation and Eutrophication

In aquaculture, maintaining optimal water quality is crucial for fish health and growth. Climate change exacerbates water quality issues through intensified rainfall and runoff, which introduce excess nutrients and pollutants into aquaculture sites, particularly in coastal regions (Ficke *et al.*, 2007) [16]. This runoff leads to eutrophication, causing algal blooms that deplete oxygen levels and produce harmful toxins, endangering fish stocks.

Hypoxic conditions can induce stress, stunt growth, and increase mortality rates in farmed fish, as seen in species like tilapia (*Oreochromis niloticus*) and catfish (*Ictalurus punctatus*). Additionally, elevated CO_2 levels contribute to acidification in freshwater and marine environments, affecting fish osmoregulation and shell formation in mollusks and crustaceans, which are also commonly farmed. Improved water treatment technologies, recirculating systems, and sustainable waste management practices are essential to mitigate the effects of water quality degradation on aquaculture under changing climatic conditions (Boyd & Tucker, 2012) [7].

3.4 Economic Implications for Fish Farmers

The economic impacts of climate change on aquaculture extend beyond increased mortality rates and reduced growth. Rising operational costs due to disease management, feed requirements, and water treatment strain the profitability of fish farms, particularly for small-scale farmers who lack resources to implement adaptive measures. In regions heavily reliant on aquaculture for income and food security, such as Southeast Asia, these challenges threaten livelihoods and local economies (Hall *et al.*, 2011) [21].

Insurance and financial support for climate adaptation remain limited for fish farmers, exacerbating their vulnerability to climate-induced disruptions. Integrating risk assessment frameworks and offering financial incentives for sustainable practices, such as climate-resilient infrastructure and selective breeding programs, can promote long-term resilience in aquaculture operations (Cochrane *et al*., 2009) [11].

4. Mitigation and Adaptation Strategies

4.1 Selective Breeding and Genetic Enhancement

Selective breeding and genetic enhancement have shown promising results in developing climate-resilient fish species for aquaculture. By focusing on traits like temperature tolerance, disease resistance, and faster growth, selective breeding enables the adaptation of farmed species to changing environmental conditions (Yáñez *et al*., 2015) [46]. Genetic programs for species like tilapia (*Oreochromis niloticus*) and salmon (*Salmo salar*) have successfully produced strains with higher tolerance to environmental stressors such as heat and low oxygen.

Advancements in genetic engineering, including CRISPR and other gene-editing techniques, open up new possibilities for accelerating resilience breeding programs, though these approaches also raise regulatory and ethical concerns (Edvardsen *et al*., 2014) [14]. As genetic modification becomes more sophisticated, considerations around ecological safety and public acceptance are essential for the effective implementation of genetic adaptation strategies in aquaculture.

4.2 Ecosystem-Based Fishery Management (EBFM)

Ecosystem-Based Fishery Management (EBFM) is a holistic approach that prioritizes the health of entire ecosystems to maintain resilient fish stocks in the face of climate change. By focusing on habitat protection, biodiversity conservation, and sustainable harvest limits, EBFM addresses the interconnected factors impacting fish populations, such as prey availability, habitat quality, and water conditions (Pikitch *et al*., 2004) [37].

Marine Protected Areas (MPAs) play a significant role in EBFM by creating refuges where fish populations can recover and sustain higher resilience to climate stressors (Halpern *et al.*, 2010) [22]. However, effective EBFM requires multi-level governance and enforcement mechanisms to ensure the success of conservation efforts and maintain ecological balance across regions (Long *et al*., 2015) [30].

4.3 Improved Aquaculture Practices

Aquaculture practices must adapt to changing environmental conditions to mitigate the impacts of climate change on farmed fish. Implementing Recirculating Aquaculture Systems (RAS) allows farms to control water quality, temperature, and oxygen levels, reducing vulnerability to external environmental changes (Martins *et al*., 2010) [31]. RAS technology has been particularly successful for temperature-sensitive species like trout and salmon, enabling stable production environments despite external climate fluctuations (Badiola *et al*., 2012) [4].

Furthermore, the integration of aquaponics and polyculture systems enhances sustainability and resilience by using waste nutrients from fish to grow plants, creating a symbiotic system that reduces environmental impact (Goddek *et al*., 2015) [19]. These systems require significant initial investment, making financial support and training essential for small-scale farmers to adopt these practices and contribute to climate-resilient aquaculture.

4.4 Habitat Restoration and Carbon Sequestration

Habitat restoration projects, including mangrove replanting, coral reef restoration, and wetland rehabilitation, help rebuild natural buffers against climate change impacts on fish populations. Mangroves, for example, sequester large amounts of carbon, mitigate coastal erosion, and provide essential nursery habitats for fish species (Alongi, 2012) [3]. Similarly, coral reef restoration not only protects biodiversity but also enhances fishery productivity by supporting fish species dependent on reef ecosystems for shelter and food.

In addition, practices such as reforestation of riparian zones around freshwater aquaculture ponds improve water quality by reducing sedimentation and nutrient runoff, promoting healthier environments for fish production. These habitat-based strategies have dual benefits for carbon sequestration and habitat protection, supporting both climate mitigation and adaptation efforts.

4.5 Policy Recommendations and Global Cooperation

Policy support is crucial for implementing climate adaptation measures in fisheries and aquaculture. International agreements like the Paris Agreement emphasize the importance of addressing climate change across sectors, including fisheries. Policy frameworks that incentivize sustainable practices, enforce fishing limits, and promote resilient fish species are essential for climate adaptation in the fishing industry (IPCC, 2019) [26].

Collaborative efforts, such as data sharing on climate impacts and coordinated marine conservation initiatives, can strengthen global responses to climate change (Barange *et al*., 2018) [5]. Regional policies, subsidies, and insurance programs tailored to small-scale fishers can also enhance resilience by providing economic security in the face of climate variability (Cochrane *et al*., 2009) [11]. Global cooperation on climate adaptation, particularly in vulnerable regions, is essential to address the transboundary impacts of climate change on fish stocks and aquaculture.

5. Future Directions and Research Needs

5.1 Enhancing Understanding of Species-Specific Responses to Climate Stressors

Future research should focus on understanding how different species respond to specific climate stressors like temperature fluctuations, hypoxia, and acidification. While studies have provided insights into the resilience of certain species, such as salmon and tilapia, the responses of many species remain unknown (Pörtner & Peck, 2010) [39]. By identifying species-specific tolerances, researchers can recommend viable species for aquaculture in regions most affected by climate change.

Additionally, as ecosystems experience multiple stressors simultaneously, research into cumulative and synergistic impacts on fish physiology, reproduction, and migration will offer a more accurate prediction of future species distributions. This understanding is particularly crucial for designing adaptation strategies tailored to individual species and local conditions (Doney *et al.*, 2012) [13].

5.2 Development of Climate-Resilient Fish Strains

The selective breeding and genetic modification of climate-resilient fish strains is a promising area of research for aquaculture. Selective breeding can improve traits like disease resistance, growth rate, and temperature tolerance, essential for adapting farmed fish to rapidly changing environments (Yáñez *et al*., 2015) [46]. The application of advanced genetic tools such as CRISPR could further accelerate the development of robust strains capable of thriving in climate-stressed conditions (Perry *et al.*, 2010) [36].

However, ethical considerations and regulatory policies surrounding genetic modification in aquaculture require continued research. Understanding public perception and ecological impacts will facilitate the responsible use of genetic technologies in the industry (Goddek *et al*., 2015) [19].

5.3 Innovations in Aquaculture Infrastructure and Technology

Investment in climate-adaptive aquaculture infrastructure, such as Recirculating Aquaculture Systems (RAS) and integrated multi-trophic aquaculture (IMTA), is essential to counteract climate impacts. RAS enables controlled environments for species requiring stable conditions, and IMTA creates symbiotic systems that enhance resilience through nutrient cycling and waste reduction (Martins *et al*., 2010; Troell *et al.*, 2009) [31, 42].

Research into reducing the costs and optimizing the efficiency of these systems can make them more accessible for small-scale farmers. Moreover, advances in water quality sensors, automated feeding systems, and real-time monitoring technologies will support more sustainable and profitable operations by minimizing the impact of climate variability on production (Schulze *et al.*, 2017) [40].

5.4 Exploring Sustainable Feed Options

With climate change affecting the availability of wild fish stocks, there is an urgent need to explore alternative feed options for aquaculture that are not only sustainable but also climate-resilient. Ingredients such as algae, insects, and plant-based proteins have shown potential as alternatives to fishmeal, reducing the environmental footprint of fish farming (Turchini *et al*., 2019) [43]. However, further research is needed to understand the long-term effects of these alternatives on fish health, growth, and product quality.

Developing balanced, affordable, and nutritionally complete feeds from sustainable sources can help address the growing demand for aquaculture without compromising ecological integrity. As feed costs constitute a significant portion of operating expenses, innovation in this area also holds economic benefits for fish farmers (Naylor *et al*., 2009) [34].

5.5 Policy Development and Collaborative Frameworks

Future climate adaptation strategies for fisheries and aquaculture require stronger policy support at both national and international levels. Policies that establish protective regulations for vulnerable habitats, promote ecosystem-based

management, and provide financial support to fishers and farmers adopting climate-adaptive practices are essential for sector resilience (Barange *et al.*, 2018) [5].
Collaborative frameworks that encourage data sharing, research collaboration, and best-practice exchange across countries will also be instrumental in addressing climate impacts on a global scale (Cochrane *et al.*, 2009) [11]. Regional and international cooperation can help standardize climate resilience efforts, supporting fish stocks and aquaculture operations worldwide.

5.6 Addressing Socioeconomic and Food Security Implications

Research into the socioeconomic effects of climate change on fisheries and aquaculture will help design policies that support vulnerable communities, particularly those in developing countries where reliance on fish for income and food security is high. Studies assessing the impacts on livelihoods, market dynamics, and fishery-dependent communities can guide policies that promote equitable and sustainable growth (Allison *et al.*, 2009) [1].
Ensuring food security through climate-resilient aquaculture is another critical area. As fish provide essential nutrients and a major protein source for millions worldwide, understanding and mitigating the food security risks associated with declining wild stocks and farmed fish yields is essential for addressing climate challenges (Golden *et al.*, 2016) [20].

6. Conclusion

Climate change presents unprecedented challenges to the sustainability of global fish stocks and aquaculture industries, affecting the ecosystems and communities dependent on fish as both a natural resource and a vital food source. This review has highlighted the multifaceted impacts of climate change on fisheries and aquaculture, spanning ocean acidification, warming temperatures, hypoxia, altered migration patterns, and increased susceptibility to diseases. These environmental shifts are not only affecting the health, distribution, and reproduction of wild fish stocks but are also introducing economic and operational uncertainties into aquaculture, a growing sector crucial for food security.
The repercussions of climate change on fish biology and ecology underline the importance of a proactive and multidisciplinary approach. Temperature increases and shifts in oceanic pH threaten the survival and distribution of many species, while warming waters and altered currents are reshaping entire ecosystems. The physiological stress induced by rising temperatures often leads to reduced growth, reproductive impairments, and lower survival rates, particularly in temperature-sensitive species. Additionally, the risks posed by diseases and parasites are exacerbated under climate stress, further challenging both wild and farmed fish populations.
In response, the review has emphasized the need for mitigation and adaptation strategies, such as the development of climate-resilient fish strains, ecosystem-based fishery management, improved aquaculture practices, and habitat restoration initiatives. Selective breeding and genetic enhancements present promising avenues for producing fish that can withstand higher temperatures, lower oxygen levels, and other climate-related stressors. However, implementing these strategies requires careful consideration of ethical, ecological, and public acceptance issues.
Furthermore, Ecosystem-Based Fishery Management (EBFM) and Marine Protected Areas (MPAs) offer pathways to conserve critical habitats and foster biodiversity resilience. By protecting vital spawning and nursery grounds, MPAs allow fish populations to replenish and sustain themselves, enhancing the resilience of marine and freshwater ecosystems. However, EBFM's success hinges on collaborative governance, stringent policy enforcement, and community involvement to balance conservation goals with economic and social needs.
Aquaculture, an essential sector for global food security, requires substantial innovation to adapt to climate impacts effectively. Technologies like Recirculating Aquaculture Systems (RAS) and integrated multi-trophic aquaculture (IMTA) offer controlled environments that mitigate external climate stresses, allowing for more consistent production despite changing environmental conditions. However, the widespread adoption of these systems depends on addressing cost and accessibility barriers, especially for small-scale producers who may lack the resources to transition to advanced systems.
The search for sustainable feed alternatives—such as algae, insect protein, and plant-based feeds—illustrates the industry's ongoing efforts to lessen reliance on wild fish stocks, which are increasingly vulnerable to climate effects. Sustainable feeds also play a crucial role in reducing the carbon footprint of aquaculture operations, aligning with broader climate mitigation goals. Nonetheless, further research is necessary to ensure that these alternatives meet nutritional standards and do not compromise fish health or product quality.
The necessity for supportive policy frameworks cannot be overstated. Policies that promote sustainable practices, enforce fishing limits, and provide financial support to fishers and farmers are fundamental to building a resilient sector. International cooperation, encompassing data-sharing initiatives, research collaborations, and standardized climate resilience guidelines, is essential to address climate impacts on a global scale, as fish stocks and aquaculture industries often cross national boundaries.
Finally, a focus on the socioeconomic dimensions of climate adaptation is critical. Fish and seafood are primary sources of nutrition and livelihoods for millions, especially in coastal and developing regions. Ensuring that these communities have the support and resources needed to adapt to climate challenges is not only a matter of economic sustainability but also one of food security and social equity. Programs that provide training, subsidies, and market access for climate-resilient practices will empower vulnerable communities to better withstand climate variability.
In conclusion, as climate change continues to reshape the world's oceans, rivers, and lakes, the resilience of fisheries and aquaculture depends on our ability to anticipate and respond to these transformations. Through a combination of scientific research, technological advancement, policy reform, and community engagement, we can mitigate the effects of climate change on these crucial sectors. However, the path forward requires sustained effort and a commitment to understanding and addressing the diverse challenges climate change imposes on aquatic ecosystems and the people who rely on them. The future of fisheries and aquaculture, and by extension global food security and biodiversity, hinges on our collective ability to adapt to an increasingly unpredictable climate.

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