Adapting to Change: Climate Impacts on Asia's Endangered Fish Populations

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ABSTRACT

Climate change has emerged as a critical factor influencing the survival and distribution of endangered fish species in Asia. This review examines the multifaceted impacts of climate change on these vulnerable aquatic populations especially fish. Rising temperatures, altered precipitation patterns, and increasing frequency of extreme weather events are reshaping freshwater ecosystems, leading to habitat loss, changes in water quality, and altered species interactions. Specifically, thermal stress from elevated water temperatures can exceed the tolerance limits of many endangered fish species, resulting in reduced fitness, altered reproductive cycles, and increased mortality rates. Changes in precipitation and runoff patterns can further exacerbate habitat degradation, leading to reduced river flows and the desiccation of critical spawning and nursery habitats. In addition to direct physiological stress, climate change amplifies existing threats such as pollution, overfishing, and habitat fragmentation. The synergistic effects of these stressors can drive population declines and increase the risk of local extinctions. The resilience of endangered fish species in Asia hinges on adaptive management strategies that incorporate climate change projections. Conservation efforts must prioritize habitat restoration, the creation of climate refugia, and the implementation of sustainable fishing practices. Additionally, integrating local and traditional knowledge with scientific research can enhance the effectiveness of conservation initiatives. Policymakers and stakeholders must collaborate to mitigate the impacts of climate change, ensuring the preservation of Asia's rich aquatic biodiversity for future generations. This review also underscores the urgent need for comprehensive research and proactive conservation measures to safeguard endangered fish species in the face of a changing climate.

Keywords: Biodiversity; climate change; conservation; ecosystem; endangered species

1. INTRODUCTION

Climate change is widely recognized as one of the most significant drivers of biodiversity loss, with aquatic ecosystems being particularly vulnerable due to their sensitivity to temperature and hydrological changes. In Asia, freshwater ecosystems are at heightened risk, given their dependency on specific temperature and flow regimes that are increasingly disrupted by climate-induced changes (Xu et al., 2021; Zheng et al., 2022). Many fish species in the region, already classified as endangered, face compounded threats from overfishing, pollution, habitat fragmentation, and the accelerating impacts of climate change. These combined pressures are creating an ecological crisis, underscoring the need for urgent and adaptive conservation measures (Chen et al., 2023).

Recent studies illustrate the cascading impacts of climate change on Asian fish populations. Rising water temperatures disrupt critical physiological and ecological processes such as growth, reproduction, and migration. Nguyen et al. (2021) documented shifts in fish distribution in the Mekong River Basin, with species migrating upstream to cooler areas, while others face restricted habitats due to thermal stress. Similarly, Jonsson (2023) found that increasing temperatures reduce metabolic efficiency in thermally sensitive fish species, exacerbating competition for limited resources and threatening population resilience. Changes in precipitation and hydrological regimes are further compounding these challenges. For example, altered seasonal flooding patterns in the Ganges-Brahmaputra River system have diminished critical spawning and nursery habitats for migratory fish, leading to declining populations (Ahmed et al., 2020).

Ocean acidification, another consequence of increased atmospheric CO2, is also impacting marine and estuarine fish populations. Acidification lowers the pH of water, impairing the ability of marine organisms to form calcium carbonate structures. This not only affects species like mollusks but also impacts fish that rely on these organisms for food or habitat, as observed in coral reef systems in Southeast Asia (Hendriks et al., 2024; Hoegh-Guldberg et al., 2021). Furthermore, extreme weather events such as typhoons, floods, and heatwaves are becoming more frequent and severe, causing habitat destruction, increased runoff pollution, and disruptions to breeding cycles (Burrows et al., 2024).

The urgency to address these challenges is heightened by global findings on climate change impacts on aquatic ecosystems. Pinsky et al. (2024) emphasized that fish species with narrow thermal tolerances and specific ecological requirements are particularly susceptible to extinction risks under changing climates. In Asia, where freshwater biodiversity underpins food security and livelihoods, the loss of aquatic species can have severe socio-economic consequences, affecting millions of people dependent on fisheries for sustenance and income (FAO, 2022; Wang et al., 2021). Additionally, disruptions in aquatic biodiversity have cascading effects on ecosystem services, such as water purification and nutrient cycling, further destabilizing regional ecological balance (Griffiths et al., 2022). Despite increasing research on climate change and its ecological impacts, there remains a critical knowledge gap in understanding how these changes specifically affect endangered fish species in Asia. Existing conservation strategies often lack the integration of localized, climate-resilient approaches informed by scientific research and traditional ecological knowledge (Chen et al., 2023; Li et al., 2023). For example, while global models predict broad-scale impacts, they fail to capture localized nuances such as community dependencies, specific ecological interactions, or regional governance limitations.

This review aims to bridge this knowledge gap by synthesizing recent research on the multifaceted impacts of climate change on Asia's endangered fish species and identifying adaptive conservation strategies tailored to regional needs. Key recommendations include habitat restoration, the establishment of climate refugia, and the promotion of sustainable fishing practices (Ahmed et al., 2020; Li et al., 2023). Integrating traditional knowledge with scientific innovation offers a promising pathway to enhance ecosystem resilience. For instance, involving local communities in conservation initiatives ensures cultural relevance and enhances the effectiveness of adaptive strategies (Xu et al., 2021; Li et al., 2022). Policymakers, researchers, and communities must collaborate to implement evidence-based measures that protect Asia's aquatic biodiversity and address the socio-economic implications of its decline. This review provides a critical foundation for guiding future research, informing policy, and advancing conservation initiatives to safeguard endangered fish populations in the face of climate change.

2. IMPACTS OF CLIMATE CHANGE

Climate change represents a profound and escalating threat to aquatic ecosystems, with particularly severe consequences for endangered fish species. Rising global temperatures are altering water conditions in both freshwater and marine environments, disrupting the delicate balance required for species survival. Changes in water temperature directly affect fish distribution, migration patterns, and reproductive cycles, often pushing species beyond their thermal tolerance limits and threatening biodiversity (Pinsky et al., 2024). Additionally, altered precipitation patterns disrupt river flows and lake dynamics, reducing habitat availability and compromising water quality for freshwater species that depend on stable ecological conditions (Dukes et al., 2024).

In marine ecosystems, ocean acidification—caused by increased atmospheric CO2—poses a significant challenge by reducing ocean pH levels. This chemical shift weakens calcium carbonate structures critical for the survival of many marine organisms, including fish that rely on such organisms for food or habitat (Hendriks et al., 2024). The physiological stress induced by acidification also impairs growth, development, and survival rates, compounding the risks faced by already vulnerable populations. Furthermore, the frequency and intensity of extreme weather events such as storms, floods, and heatwaves have increased due to climate change. These events lead to habitat destruction, heightened pollution runoff, and disruption of breeding and feeding behaviors, creating cascading effects on aquatic ecosystems (Burrows et al., 2024). For instance, heatwaves can trigger mass fish mortality events by causing abrupt oxygen depletion in water bodies, while severe storms often destroy spawning grounds critical for species regeneration. When combined with anthropogenic pressures like overfishing, habitat degradation, and pollution, these climate-induced stressors create a compounding effect, exacerbating the vulnerabilities of aquatic species. The cumulative impact of these factors (Table 1) underscores the urgent need for a holistic approach to conservation. Adaptive management strategies, integrating climate resilience measures, habitat restoration, and stricter regulation of human activities, are essential to safeguard aquatic biodiversity and ensure the long-term stability of these ecosystems.

2.1 Temperature Rise and Habitat Alteration

Many fish species are sensitive to temperature changes, as their metabolic rates, reproductive cycles, and distribution are closely tied to specific thermal conditions (Beitinger et al. 2000). These thermal preferences are crucial for their survival, growth, and reproduction, and even minor temperature fluctuations can significantly impact their physiological functions and behaviors (Pörtner & Farrell 2008). For instance, certain fish species may experience altered spawning times or reduced reproductive success when exposed to temperatures outside their optimal range (Daufresne et al. 2009). Additionally, temperature changes can influence fish distribution, often causing species to migrate to more favorable environments or face increased competition and predation in their native habitats (Crozier & Hutchings 2014). Recent studies have also highlighted the importance of understanding thermal ecology to predict fish responses to ongoing climate change and to develop effective conservation strategies (Neuheimer et al. 2022). In the following, we will provide case studies that illustrate the impacts of temperature changes on various endangered fish species, highlighting both observed and projected effects in different aquatic ecosystems

2.1.1 Mekong Giant Catfish (Pangasianodon gigas). The *Pangasianodon gigas*, a critical species in Southeast Asia’s Mekong River Basin, is suffering from the effects of altered river flow patterns and increasing temperatures. The construction of dams and water diversion projects has disrupted natural river flows, impacting the catfish's breeding and migration cycles. These changes, combined with rising temperatures that affect water quality and stress the fish, are severely disrupting the catfish’s reproductive success. Hogan et al. (2024) highlight that these environmental changes are leading to reduced spawning grounds and altered migration patterns, which threaten the survival of this iconic species.

2.1.2 Arctic Char (Salvelinus alpinus). The *Salvelinus alpinus*, native to cold-water habitats in Arctic and sub-Arctic regions, faces significant challenges due to rising temperatures. As global temperatures increase, the cold-water environments essential for Arctic char are shrinking, leading to habitat loss and fragmentation. Melting ice and altered river patterns are further isolating populations, which reduces genetic diversity and disrupts ecological balances. Additionally, warming temperatures are allowing more thermally tolerant species to invade Arctic char habitats, leading to increased competition for resources. According to Reist (2023), these factors are contributing to declines in Arctic char populations and changes in their distribution.

2.1.3 Coho Salmon (Oncorhynchus kisutch). Coho salmon are particularly sensitive to temperature increases during their freshwater life stages. A study by Beechie et al. (2012) showed that warming stream temperatures in the Pacific Northwest of the United States have resulted in reduced juvenile survival rates. The loss of cold-water habitats has forced coho salmon to migrate to higher elevations or more northerly latitudes, which may not always provide suitable conditions for their lifecycle. This shift has implications for their long-term survival and reproductive success.

2.1.4 Sockeye Salmon (Oncorhynchus nerka). Sockeye salmon are highly vulnerable to rising temperatures, particularly during their migration and spawning periods. Research by Hinch et al. (2012) indicated that higher river temperatures during migration can lead to increased mortality due to thermal stress and disease susceptibility. In extreme cases, these elevated temperatures can prevent salmon from reaching their spawning grounds altogether, leading to significant population declines. The Fraser River in British Columbia, Canada, has seen notable reductions in sockeye salmon returns, which have been attributed in part to warmer river conditions.

2.1.5 Delta Smelt (Hypomesus transpacificus). The Delta smelt, a small fish endemic to the Sacramento-San Joaquin Delta in California, is critically endangered and has been profoundly impacted by rising temperatures. Feyrer et al. (2011) found that higher water temperatures, coupled with changes in salinity and flow patterns, have led to a significant reduction in the smelt's habitat range. The altered environmental conditions have affected their reproductive success and larval survival rates, contributing to the species' rapid decline.

2.1.6 Golden Mahseer (Tor putitora). The golden mahseer, found in the Himalayan region, is another species facing severe threats from climate change. Nautiyal et al. (2008) reported that rising river temperatures and changing precipitation patterns have negatively impacted the mahseer's spawning cycles and juvenile development. The combination of thermal stress and habitat fragmentation due to altered river flows has led to a decline in golden mahseer populations across their native range.

2.1.7 Sturgeon (Acipenseridae Family). Sturgeons, ancient and ecologically significant fish species, are highly sensitive to environmental changes, particularly temperature fluctuations. The endangered *Acipenser oxyrinchus* has been notably impacted by warming waters in the Hudson River, USA. Secor & Gunderson (1998) reported that rising water temperatures have disrupted sturgeon migration patterns and diminished the availability of suitable spawning habitats. These changes, coupled with additional pressures such as habitat loss and overfishing, have exacerbated the decline in sturgeon populations.

2.1 Ocean Acidification

Ocean acidification refers to the reduction in the pH of the Earth's oceans caused primarily by the uptake of carbon dioxide (CO_2) from the atmosphere. As CO_2 levels increase, more CO_2 is absorbed by seawater, forming carbonic acid which lowers the pH, making the oceans more acidic. This process can significantly impact marine life, particularly fish, by affecting their sensory abilities, reproduction, and growth rates. Acidified waters can interfere with fish's ability to detect predators, find food, and communicate, leading to higher mortality rates and disrupted ecosystems. Recent studies, such as those by McMahon et al. (2023), have shown that prolonged exposure to acidified conditions can alter fish behavior and physiology, posing a serious threat to marine biodiversity and fisheries globally. Next, the section explores case studies demonstrating the consequences of ocean acidification on several endangered fish species, emphasizing both observed and anticipated repercussions across different aquatic environments.

2.2.1 Coral Trout (Plectropomus leopardus). A study by Munday et al. (2014) investigated how ocean acidification affects the coral trout, a key predator in coral reef ecosystems. The researchers found that increased CO_2 levels significantly impair the fish's foraging behavior and sensory functions. Coral trout exposed to acidified conditions exhibited reduced ability to locate prey and increased aggression towards conspecifics, which could disrupt reef dynamics and food webs. This study highlights how acidification can affect predator-prey interactions and potentially destabilize entire reef ecosystems.

2.2.2 European Sea Bass (Dicentrarchus labrax). The impact of ocean acidification on European sea bass was examined by Milazzo et al. (2018). Their research focused on how elevated CO_2 levels affect the development and behavior of sea bass larvae. The study found that acidification led to altered growth rates, increased mortality, and impaired sensory and cognitive functions. Larvae exposed to high CO_2 levels showed reduced swimming performance and altered predator recognition abilities, which could impact their survival and recruitment into adult populations.

2.2.3 Blue Tang (Paracanthurus hepatus). The effects of ocean acidification on the blue tang, a species popularized by the film "Finding Nemo," were studied by Clements et al. (2016). Their research showed that acidification negatively affects the fish's ability to navigate and avoid predators. The study demonstrated that increased CO_2 levels impair the blue tang's spatial learning and memory, which are essential for navigating complex coral reef environments. This impairment could lead to reduced survival rates and affect the overall health of coral reef ecosystems.

2.2.4 Sockeye Salmon (Oncorhynchus nerka). Ocean acidification's effects on sockeye salmon, a species crucial to the Pacific Northwest ecosystems, were investigated by Sunday et al. (2016). The study found that acidification affects the fish's early developmental stages, particularly during the larval and juvenile phases. Elevated CO2 levels led to reduced growth rates, impaired sensory and motor functions, and altered migratory behaviors. These effects have potential consequences for sockeye salmon populations and their role in the marine food web.

2.2.5 Napoleon Wrasse (Cheilinus undulatus). The critically endangered Napoleon wrasse, a large and long-lived coral reef fish, has also been shown to be highly vulnerable to ocean acidification. Eyre et al. (2014) focused on the effects of elevated CO_2 on the growth and survival of juvenile Napoleon wrasse. Their research indicated that acidification disrupts normal growth rates and development. The study revealed that juvenile Napoleon wrasse exposed to high CO_2 levels grew more slowly and were more susceptible to predation. These effects are attributed to changes in metabolic rates and sensory perception, which are critical for detecting and avoiding predators. The study underscores the vulnerability of early life stages of this species and suggests that ongoing acidification could lead to significant declines in populations.

2.2.6 Great Barrier Reef Fish Community. Ocean acidification also poses threats to broader fish communities in coral reef ecosystems, as demonstrated by Ferrari et al. (2011). The study focused on the Great Barrier Reef and examined how acidification affects fish behavior and interactions. The researchers found that increased CO_2 levels altered the behavior of reef fish, including their ability to recognize predators and navigate their environment. For instance, fish exposed to acidified conditions were less effective at locating shelter and avoiding predators, leading to higher mortality rates. The study also highlighted that changes in fish behavior could disrupt the balance of the entire reef ecosystem, impacting species interactions and the health of coral reefs. This research emphasizes the interconnectedness of coral reef communities and the cascading effects of ocean acidification on both endangered and non-endangered species.

2.2.7 Damselfish (Pomacentrus spp.). A comprehensive study by Dixson et al. (2010) explored the impact of ocean acidification on damselfish, which are commonly found on coral reefs. The researchers found that increased CO_2 levels led to altered predator-prey interactions, with damselfish becoming less cautious and more prone to predation. The study also highlighted changes in social behavior, as acidified conditions led to reduced aggression and social interactions within groups. These behavioral changes could have significant implications for reef community dynamics and the conservation of these species.

2.2.8 Clownfish (Amphiprion percula). Ocean acidification significantly affects clownfish, an iconic species of coral reef fish. A seminal study by Munday et al. (2010) investigated how elevated CO_2 levels disrupt the sensory and cognitive functions of clownfish. The researchers exposed juvenile clownfish to increased CO_2 concentrations and found that these fish exhibited altered behavior patterns, such as reduced ability to recognize and avoid predators. This behavioral change stems from the impact of acidification on their sensory systems, particularly their olfactory and auditory cues. Additionally, these fish showed decreased activity levels and increased anxiety, leading to higher mortality rates and lower reproductive success. The study highlights how ocean acidification impairs key behaviors that are crucial for survival and reproductive success, thereby affecting the population dynamics of this endangered species.

2.2 Freshwater Acidification

Freshwater acidification occurs when the pH levels of water bodies decrease due to atmospheric pollutants like sulfur and nitrogen oxides, commonly from acid rain. This process is exacerbated by climate change, which influences temperature, precipitation patterns, and atmospheric CO_2 levels, all of which intensify acidification. Increased CO_2, when absorbed by freshwater, forms carbonic acid, further lowering pH levels (Lindh et al., 2023). Additionally, climate change enhances acid rain through rising temperatures and greater precipitation, compounding the effects on aquatic ecosystems. Endangered freshwater fish species, which are highly sensitive to changes in water chemistry, are particularly vulnerable. Acidification impairs their ability to regulate internal pH, affecting growth, reproduction, and survival. Research shows that acidified waters can reduce fish diversity, alter community structures, and disrupt food webs and ecosystem functions (Weyhenmeyer et al., 2024; Evans et al. 2023).

2.3.1 Mahseer (Tor tambroides). A study by Iskandar et al. (2023) titled "Elevated Carbon Dioxide and Its Impact on Growth, Blood Properties, and Vertebral Column of Freshwater Fish Mahseer, *Tor tambroides* Juveniles" investigated the effects of increased CO_2 levels on the growth, physiology, and skeletal structure of Mahseer juveniles. The researchers found that exposure to elevated CO_2 concentrations significantly affected the fish's growth rate, causing stunted development. Changes in blood properties, such as decreased oxygen-carrying capacity, were also observed. Additionally, skeletal deformities in the vertebral column were documented, indicating that acidification could severely compromise the health and survival of this species. This study highlights the vulnerability of Mahseer to freshwater acidification, calling for urgent conservation efforts to mitigate these impacts on this culturally and economically important species.

2.3.2 Atlantic Salmon (Salmo salar). A study by the International Union for Conservation of Nature (IUCN) in 2023 reported that Atlantic salmon are facing growing challenges due to climate change-induced freshwater acidification. Acidification affects salmon at various stages of their life cycle, particularly during spawning and juvenile development. Reduced prey availability and the intrusion of invasive species, such as the Pacific pink salmon, further threaten their populations. The study also highlighted that the global population of Atlantic salmon has declined by 23% between 2006 and 2020, leading to a Near Threatened status (Crozier, 2019).

2.3.3 Arctic Grayling (Thymallus arcticus). A recent study on Arctic grayling published by PLOS Climate in 2023 found that freshwater acidification, along with warming water temperatures, significantly affects the survival and reproduction rates of this species in Alaska and Canada. The early life stages are particularly vulnerable, with acidification reducing the abundance of aquatic insects, the primary food source for juvenile grayling. These findings suggest that combined climate stressors could accelerate the decline of Arctic grayling populations (Murdoch et al., 2021).

2.3.4 White Sturgeon (Acipenser transmontanus). A 2022 study on white sturgeon found that freshwater acidification disrupts sensory functions and reduces food availability in rivers like the Columbia and Fraser. These changes threaten the recovery of white sturgeon populations, which are already endangered due to habitat degradation and overfishing. Acidified water conditions interfere with sturgeon's ability to locate prey, reducing growth rates and reproductive success (Kynard & Horgan, 2002).

2.3.5 Lake Trout (Salvelinus namaycush). Lake trout in North American freshwater ecosystems have shown declining population trends due to acidification and rising water temperatures. A 2022 report on inland fishes revealed that lower pH levels impair the ability of lake trout to successfully reproduce, leading to higher egg mortality rates. Acidification also reduces the availability of calcium, essential for the development of juvenile trout (Al-Chokhachy et al., 2017).

2.3.6 Arctic Grayling (Thymallus arcticus). Parker & Schindler (2006) investigated the effects of freshwater acidification on Arctic grayling in Alaska and Northern Canada. The study found that acidification reduced prey availability and growth rates in juvenile grayling, contributing to population declines. This research highlights the compounding effects of climate change and acidification on this vulnerable species.

2.3.7 White Sturgeon (Acipenser transmontanus). A study by Kynard & Horgan (2002) examined the effects of water chemistry changes, including acidification, on white sturgeon populations in the Pacific Northwest. The researchers found that acidified waters disrupted the food web by reducing plankton populations, leading to lower growth rates and reproductive success in white sturgeon. This study emphasizes the threats freshwater acidification poses to this endangered species.

Table 1. Impacts of Climate Change on Endangered Fish Species in Asia: Key Findings and Case Studies.

Section	Climate Change Impacts	Endangered Fish Species Affected	Research Results	References
A	Temperature Rise and Habitat Alteration	Mekong Giant Catfish (*Pangasianodon gigas*)	Highlight that these environmental changes are leading to reduced spawning grounds and altered migration patterns, which threaten the survival of this iconic species.	Hogan et al. (2024)
		Arctic Char (*Salvelinus alpinus*)	These factors are contributing to declines in Arctic char populations and changes in their distribution.	Reist (2023)
		Coho Salmon (*Oncorhynchus kisutch*)	This shift has implications for their long-term survival and reproductive success.	Beechie et al. (2012)
		Sockeye Salmon (*Oncorhynchus nerka*)	Higher river temperatures during migration can lead to increased mortality due to thermal stress and disease susceptibility. In extreme cases, these elevated temperatures can prevent salmon from reaching their spawning grounds altogether, leading to significant population declines	Hinch et al. (2012)
		Delta Smelt (*Hypomesus transpacificus*)	The altered environmental conditions have affected their reproductive success and larval survival rates, contributing to the species' rapid decline.	Feyrer et al. (2011)

		Golden Mahseer (*Tor putitora*)	Rising river temperatures and changing precipitation patterns have negatively impacted the mahseer's spawning cycles and juvenile development.	Nautiyal et al. (2008)
		Sturgeon (*Acipenseridae Family*)	Increased water temperatures have altered sturgeon migration patterns and reduced suitable spawning habitats.	Secor & Gunderson (1998)
B	OceanAcidification	Coral Trout (*Plectropomus leopardus*)	Increased CO_2 levels significantly impair the fish's foraging behavior and sensory functions. It also highlights how acidification can affect predator-prey interactions and potentially destabilize entire reef ecosystems.	Munday et al. (2014)
		European Sea Bass (*Dicentrarchus labrax*)	Acidification led to altered growth rates, increased mortality, and impaired sensory and cognitive functions Larvae exposed to high CO_2 levels showed reduced swimming performance and altered predator recognition abilities, which could impact their survival and recruitment into adult populations	Milazzo et al. (2018)
		Blue Tang (*Paracanthurus hepatus)*	Increased CO_2 levels impair the blue tang's spatial learning and memory, which are essential for navigating complex coral reef	Clements et al. (2016)

		environments. This impairment could lead to reduced survival rates and affect the overall health of coral reef ecosystems.	
	Sockeye Salmon (*Oncorhynchus nerka*)	Acidification affects the fish's early developmental stages, particularly during the larval and juvenile phases. Elevated CO2 levels led to reduced growth rates, impaired sensory and motor functions, and altered migratory behaviors. These effects have potential consequences for sockeye salmon populations and their role in the marine food web.	Sunday et al. (2016)
	Napoleon Wrasse (*Cheilinus undulatus*)	Fish in high CO2 levels grew more slowly and were more susceptible to predation. These effects are attributed to changes in metabolic rates and sensory perception, which are critical for detecting and avoiding predators. The study underscores the vulnerability of early life stages of this species and suggests that ongoing acidification could lead to significant declines in population	Eyre et al. (2014)
	Great Barrier Reef Fish Community	Increased CO_2 levels altered the behavior of reef fish, including their ability to recognize predators and navigate their environment. For instance, fish exposed	Ferrari et al. (2011)

		to acidified conditions were less effective at locating shelter and avoiding predators, leading to higher mortality rates. The study also highlighted that changes in fish behavior could disrupt the balance of the entire reef ecosystem, impacting species interactions and the health of coral reefs. This research emphasizes the interconnectedness of coral reef communities and the cascading effects of ocean acidification on both endangered and non-endangered species.	
	Damselfish (*Pomacentrus spp*.)	Increased CO_2 levels led to altered predator-prey interactions, with damselfish becoming less cautious and more prone to predation. The study also highlighted changes in social behavior, as acidified conditions led to reduced aggression and social interactions within groups. These behavioral changes could have significant implications for reef community dynamics and the conservation of these species	Dixson et al. (2010)
	Clownfish (*Amphiprion percula*)	Increased CO_2 concentrations and found that these fish exhibited altered behavior patterns, such as reduced ability to recognize and avoid predators. This	Munday et al. (2010)

			behavioral change stems from the impact of acidification on their sensory systems, particularly their olfactory and auditory cues. Additionally, these fish showed decreased activity levels and increased anxiety, leading to higher mortality rates and lower reproductive success. The study highlights how ocean acidification impairs key behaviors that are crucial for survival and reproductive success, thereby affecting the population dynamics of this endangered species.	
C	Freshwater Acidification	Mahseer (*Tor tambroides*)	Increased CO_2 levels on the growth, physiology, and skeletal structure of Mahseer juveniles. The researchers found that exposure to elevated CO2 concentrations significantly affected the fish's growth rate, causing stunted development. Changes in blood properties, such as decreased oxygen-carrying capacity, were also observed. Additionally, skeletal deformities in the vertebral column were documented, indicating that acidification could severely compromise the health and survival of this species. This study highlights the vulnerability of Mahseer to freshwater acidification, calling for urgent conservation	Iskandar et al. (2023)

		efforts to mitigate these impacts on this culturally and economically important species.	
	Atlantic Salmon (*Salmo salar*)	Acidification affects salmon at various stages of their life cycle, particularly during spawning and juvenile development. Reduced prey availability and the intrusion of invasive species, such as the Pacific pink salmon, further threaten their populations.	Crozier (2019)
	Arctic Grayling (*Thymallus arcticus*)	Acidification reducing the abundance of aquatic insects, the primary food source for juvenile grayling. These findings suggest that combined climate stressors could accelerate the decline of Arctic grayling populations	Murdoch et al. (2021)
	White Sturgeon (*Acipenser transmontanus*)	Freshwater acidification disrupts sensory functions and reduces food availability in rivers like the Columbia and Fraser. Acidified water conditions interfere with sturgeon's ability to locate prey, reducing growth rates and reproductive success	Secor & Gunderson (1998)
	Lake Trout (*Salvelinus namaycush*)	Ecosystems have shown declining population trends due to acidification	Al-Chokhachy et al. (2017)

		nland fishes revealed that lower pH levels impair the ability of lake trout to successfully reproduce, leading to higher egg mortality rates. Acidification also reduces the availability of calcium, essential for the development of juvenile trout	
	Arctic Grayling (*Thymallus arcticus*)	Acidification reduced prey availability and growth rates in juvenile grayling, contributing to population declines. This research highlights the compounding effects of climate change and acidification on this vulnerable species.	Schindler & Smol (2006)
	White Sturgeon (*Acipenser transmontanus*)	Acidified waters disrupted the food web by reducing plankton populations, leading to lower growth rates and reproductive success in white sturgeon. This study emphasizes the threats freshwater acidification poses to this endangered species	Kynard & Horgan (2002)

The survival challenges faced by endangered fish species directly impact on the achievement of several Sustainable Development Goals (SDGs) (Figure 1), highlighting their critical role in biodiversity conservation and sustainable development. Species such as the Mekong Giant Catfish (*Pangasianodon gigas*), which suffer from reduced spawning grounds due to altered river flows and rising temperatures, are emblematic of threats to SDG 14 (Life Below Water). The decline of keystone species like this disrupts aquatic ecosystems, reducing their ability to support diverse life forms and sustain ecological balance. Similarly, the Sockeye Salmon (*Oncorhynchus nerka*), highly sensitive to elevated river temperatures, faces migration and spawning challenges, resulting in population declines that further destabilize aquatic biodiversity. Coral Trout (*Plectropomus leopardus*), impacted by ocean acidification, exemplifies how climate stressors can impair behavior and ecosystem dynamics. These disruptions undermine predator-prey relationships and destabilize coral reef systems, critical habitats for countless marine organisms. The loss of species like the Mahseer (*Tor tambroides*), affected by freshwater acidification and hydrological changes, demonstrates the direct consequences of climate-induced stress on culturally and economically significant freshwater fish.

These species-specific challenges also intersect with SDG 13 (Climate Action), emphasizing the urgent need for climate mitigation and adaptation strategies. Reducing CO2 emissions and implementing resilience-focused conservation measures are essential to protect these species from the escalating impacts of climate change. Furthermore, species declines have socio-economic implications tied to SDG 2 (Zero Hunger) and SDG 1 (No Poverty). For instance, the decline of species like the Delta Smelt (*Hypomesus transpacificus*) and Golden Mahseer (*Tor putitora*) threatens food security and livelihoods for communities dependent on fisheries. Protecting these species ensures the sustainability of vital resources for small-scale fishers and vulnerable populations. The conservation of endangered species like the Mekong Giant Catfish, Sockeye Salmon, Coral Trout, Mahseer, and others is integral to achieving SDGs. These species are not only vital for maintaining biodiversity but also for supporting human communities, underscoring the importance of integrating conservation efforts into the broader sustainability agenda.

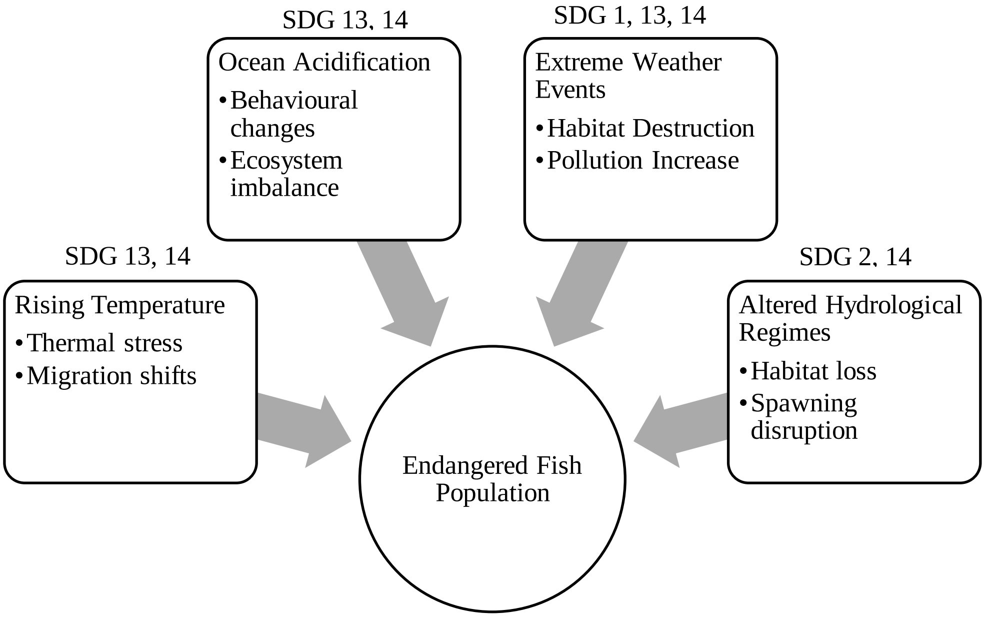

Figure 1. Linking climate change factors to challenges facing endangered fish species and SDGs.

3. ADAPTIVE MANAGEMENT STRATEGIES

Adaptive management strategies are essential to mitigating the impacts of climate change on endangered fish species, as summarized in Figure 2. These strategies involve a dynamic process of monitoring, evaluating, and adjusting management actions based on new information and changing conditions. In Asia, several mitigation strategies have been implemented, such as habitat restoration projects, fishery regulations, and community-based co-management initiatives. For example, habitat restoration efforts in the Mekong River Basin have aimed to counter the impacts of altered flow regimes, while stricter fishing quotas in the Yangtze River have sought to alleviate overfishing pressures. However, significant gaps remain, including limited integration of climate projections into planning, inconsistent enforcement of regulations, and insufficient stakeholder engagement in some regions. Incorporating climate change projections into these strategies is crucial to enhance their effectiveness. Adaptive approaches should address these gaps by including region-specific climate models to predict future habitat changes, promoting transboundary collaboration for migratory species, and integrating traditional ecological knowledge with scientific research. These enhancements will ensure conservation efforts are more resilient to ongoing and future environmental changes, ultimately supporting the long-term survival of endangered fish populations in Asia.

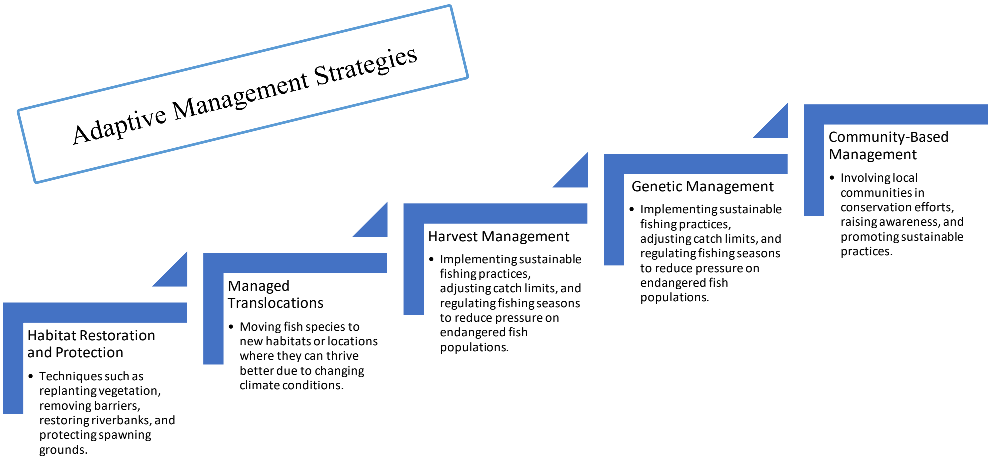

Figure 2. Adaptive management strategies for mitigating climate change impacts on endangered fish species.

3.1 Habitat Restoration and Protection

One critical adaptive management strategy is the restoration and protection of fish habitats. Climate change often alters water temperatures, flow regimes, and the availability of critical habitats. Fish species have specific thermal preferences, and deviations from these can lead to increased stress and mortality. By protecting and restoring riparian zones and wetlands, managers can create thermal refuges and buffer against temperature extremes. For instance, riparian vegetation can provide shade, reducing water temperatures in streams and rivers. A study by Crozier et al. (2019) demonstrated that riparian restoration in the Pacific Northwest of the United States can moderate stream temperatures, benefiting species such as the endangered Chinook salmon. This approach is supported by climate projections that indicate increasing temperatures and altered precipitation patterns, which will likely exacerbate thermal stress in aquatic ecosystems.

Moreover, habitat restoration efforts should consider future climate scenarios to ensure long-term effectiveness. This involves identifying and prioritizing areas for conservation that are expected to remain suitable under future climatic conditions. Tools such as species distribution models can help predict how habitats will shift and guide restoration efforts. For example, efforts to restore floodplains and reconnect rivers with their floodplains can enhance habitat complexity, providing refuges for fish during extreme weather events, such as floods and droughts, which are expected to become more frequent with climate change.

3.2 Managed Translocations

Another adaptive strategy is the implementation of managed translocations, where fish populations are relocated to habitats predicted to remain suitable under future climate scenarios. This approach requires detailed climate modeling to identify potential refuge habitats that will maintain appropriate conditions as the climate changes. For instance, research conducted by Al-Chokhachy et al. (2017) on bull trout (*Salvelinus confluentus*) in the western United States showed that translocating individuals to cooler headwater streams could provide a viable strategy for maintaining populations as lower elevation habitats warm. Managed translocations can also be used to establish new populations in areas where conditions are expected to improve due to climate change, thus expanding the range of endangered species and enhancing their resilience.

However, managed translocations come with risks, such as the potential for spreading diseases or disrupting local ecosystems. Therefore, it is crucial to conduct thorough assessments of both source and target habitats and to monitor translocated populations to ensure their success. Additionally, engaging local communities and stakeholders in the translocation process can help address social and ecological concerns and increase the likelihood of success.

3.3 Harvest Management

Incorporating climate change projections into fishery management practices can also help mitigate climate impacts. Adaptive harvest management adjusts fishing pressure based on real-time monitoring and future climate projections, ensuring sustainable fish populations. For example, the International Pacific Halibut Commission (IPHC) has integrated climate models into its stock assessment process to account for changes in ocean temperatures and productivity. This allows for more accurate setting of catch limits that consider both current stock status and future climate impacts.

Adaptive harvest management involves continuous data collection and analysis to detect changes in fish populations and their habitats. By incorporating environmental indicators such as water temperature, flow rates, and habitat conditions, managers can make informed decisions about harvest levels and timing. This approach reduces the risk of overfishing during periods of environmental stress and helps maintain healthy fish populations.

3.4 Genetic Management Strategies

Genetic management strategies that enhance the resilience of fish populations to climate change are increasingly important. Conservation breeding programs can prioritize genetic diversity, which provides the raw material for natural selection and adaptation. For instance, studies on salmonids have shown that maintaining high genetic diversity can enhance population resilience to temperature and flow changes. Hansen et al. (2018) emphasize the importance of genetic monitoring and the use of climate-adaptive breeding protocols to ensure the long-term viability of endangered fish populations.

Genetic management can involve selecting individuals with traits that confer greater resilience to climate change, such as tolerance to higher temperatures or altered flow regimes. These individuals can then be used in breeding programs to enhance the overall resilience of the population. Additionally, genetic monitoring can help detect changes in genetic diversity and structure over time, allowing managers to adjust their strategies as needed.

3.5 Community-Based Management

Community-based management that involves local stakeholders in the decision-making process can enhance the effectiveness of adaptive strategies. Local communities often possess valuable traditional ecological knowledge and are directly affected by climate change impacts on fish resources. Engaging these communities in adaptive management efforts can lead to more effective and socially acceptable solutions. For example, the participatory management approach used in the Mekong River Basin has improved the resilience of fish populations by integrating local knowledge with scientific data and climate projections. Community-based management involves creating partnerships between government agencies, non-governmental organizations, and local communities to collaboratively manage fish resources. This approach can increase the capacity for monitoring and enforcement, as well as foster a sense of stewardship among local communities. By incorporating local knowledge and values into management plans, adaptive strategies can be more culturally appropriate and better supported by the communities they aim to benefit.

To address the challenge of generalized policy recommendations, tailoring these community-based approaches to specific socio-economic, cultural, and governance contexts is critical. Asia’s diverse landscape requires region-specific strategies that reflect local realities. For example, in coastal nations such as Indonesia and the Philippines, where small-scale fisheries dominate, adaptive strategies should focus on strengthening the role of local fisher associations and providing financial incentives for sustainable practices. By contrast, in landlocked regions like Laos or certain parts of India, efforts could prioritize the conservation of freshwater habitats and the inclusion of marginalized groups, such as women and indigenous fishers, in resource management decisions. Recognizing and integrating traditional ecological knowledge into formal governance frameworks is particularly relevant in countries with strong indigenous stewardship traditions, such as Malaysia and Thailand.

Furthermore, these efforts must align with existing governance structures and regional conservation policies to ensure broader applicability and scalability. For instance, the decentralized fisheries management systems in the Philippines could serve as a model for empowering local authorities while ensuring their efforts are supported by national policies. Such alignment not only enhances the effectiveness of community-based management but also provides a mechanism for addressing transboundary challenges, such as migratory fish populations and shared water resources.

To make these strategies actionable, governments and non-governmental organizations should invest in capacity-building initiatives that empower local stakeholders. This includes training programs, funding opportunities, and access to technology that improves resource monitoring and enforcement. Integrating innovative tools, such as real-time reporting apps or GIS-based mapping, with local knowledge allows for more precise and adaptive decision-making. Regional knowledge-sharing platforms can also facilitate the exchange of best practices, fostering collaboration across countries to address shared challenges effectively.

Embedding community-based management into tailored, region-specific policy frameworks that consider socio-economic, cultural, and governance factors can bridge the gap between strategy and implementation. By ensuring that adaptive strategies are locally relevant and inclusive, while also supported by broader institutional frameworks, we can create conservation policies that are both effective and sustainable. This approach not only safeguards Asia's aquatic biodiversity but also empowers communities, ensuring equitable and lasting benefits in the face of climate change.

4. CONCLUSION

In conclusion, the implementation of adaptive management strategies is imperative to mitigate the impacts of climate change on endangered fish species in Asia. By restoring and protecting habitats, implementing managed translocations, adjusting fishery practices, enhancing genetic resilience, and involving local communities, we can develop robust management plans that safeguard fish populations in a changing climate. These strategies require continuous monitoring, flexibility, and collaboration among various stakeholders to be effective. Moving forward, integrating climate change adaptation into national and regional conservation policies is essential, aligning these efforts with the Sustainable Development Goals (SDGs). For instance, establishing climate-resilient aquatic protected areas directly supports SDG 14 (Life Below Water) by conserving marine biodiversity and protecting critical habitats. Strengthening research on the genetic adaptation of fish species to climate change will not only enhance our understanding but also contribute to SDG 13 (Climate Action) by enabling the development of effective climate resilience strategies. Furthermore, fostering community engagement and empowering local stakeholders aligns with SDG 1 (No Poverty) and SDG 2 (Zero Hunger) by promoting sustainable fisheries management that can improve livelihoods and food security. Educating communities about the importance of sustainable fishing practices, habitat conservation, and climate change adaptation can create a sense of stewardship, ensuring the long-term survival of endangered fish species. Collaborating among governments, researchers, NGOs, and indigenous communities will support SDG 17 (Partnerships for the Goals) by developing comprehensive solutions that address climate change challenges, ultimately ensuring that endangered fish species thrive, ensuring the long-term resilience of Asia's aquatic ecosystems.

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