Climate Change Impacts on Inland and Black Sea Marine Fisheries: Risks, Adaptation, and Sustainable Investment Pathways

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Abstract

This paper explores climate adaptation and sustainable investment strategies within the fisheries and aquaculture sectors, with a focus on vulnerable regions such as the Black Sea basin. As climate change intensifies environmental pressures and socioeconomic vulnerabilities, building resilience requires an integrated approach combining localized adaptation, mitigation and strategic investment. The discussion highlights practical adaptation measures for aquaculture communities, including species diversification, climate-resilient infrastructure, ecosystem-based solutions and inclusive governance reforms. Simultaneously, mitigation efforts, such as reducing emissions from feed production and promoting renewable energy, remain essential to long-term sustainability.

The paper also outlines five key investment pillars critical for climate-aligned transformation: green infrastructure, cold chain systems, research and extension services, financial risk management, and inclusive public-private partnerships. Emphasis is placed on the importance of blended investment models and enabling legal and policy frameworks that ensure equitable participation and ecosystem restoration. By aligning economic development with ecological limits, sustainable investment in fisheries and aquaculture can serve as a driver of blue growth, biodiversity conservation and community resilience. The findings underscore the urgency of integrated, forward-thinking policies and the value of adaptive, locally informed approaches in advancing climate-resilient food systems.

Keywords: Climate-smart fisheries, Inland and Marine fisheries, Aquaculture resilience, Adaptation, Investment pathways, Black Sea region.

Introduction

Fisheries and aquaculture play a vital role in global food security, livelihoods and ecosystem services. These sectors are increasingly threatened by the compounding effects of climate change, environmental degradation and unsustainable practices. From ocean warming and acidification to freshwater scarcity and habitat loss, the impacts are multifaceted, posing risks to species survival, production stability and socio-economic resilience. These challenges are particularly acute in climate-sensitive and biodiverse regions such as the Black Sea basin, where both inland and marine fisheries are undergoing profound ecological shifts.

The urgency of climate action in aquatic food systems is now widely recognized in global development agendas, including the Sustainable Development Goals (SDGs), the Paris Agreement, and national climate adaptation plans. However, the response remains uneven, and often disconnected from local needs and realities. Building resilience in fisheries and aquaculture requires not only technical solutions but also a holistic framework that combines adaptation, mitigation and inclusive investment. This includes fostering innovation in climate-smart production systems, strengthening ecosystem-based management and improving access to financial and knowledge-based resources.

This paper examines the dynamic interplay between climate stressors and aquatic food systems, with a focus on adaptation and sustainable investment pathways. Drawing on regional examples and emerging best practices, it identifies actionable strategies to enhance the resilience and sustainability of fisheries and aquaculture. The analysis is organized around key thematic areas: climate impacts on inland and marine ecosystems, community-level adaptation options and strategic investment pillars necessary for climate-aligned development. Special attention is given to the Black Sea region as a case study that reflects broader global challenges and opportunities. Ultimately, this paper aims to contribute to a more integrated and forward-looking approach to climate-resilient development in the blue economy.

Methodology / Analytical Approach

This article is grounded in a qualitative desk review and synthesis of secondary literature, focused on identifying climate risks, adaptive responses, and sustainable investment approaches in fisheries and aquaculture systems. The analysis draws from a wide range of scholarly publications, institutional reports, and policy briefs, aiming to distill actionable insights and regionally applicable strategies, particularly in the context of the Black Sea basin and other climate-sensitive aquatic ecosystems.

Key data sources included technical publications from the Food and Agriculture Organization of the United Nations (FAO), thematic studies by Maulu et al. (2021), and strategic investment guidance from the Columbia Center on Sustainable Investment (CCSI). These materials provided foundational perspectives on ecosystem-based adaptation, the implications of climate change for aquaculture sustainability and the development of climate-smart technologies and governance frameworks aligned with the Sustainable Development Goals (SDGs).

In addition, the study incorporated expert materials, case studies and training content developed through academic collaborations with the University of Idaho and Mississippi State University. These contributions included practice-based insights on climate-resilient aquaculture systems, trout farming under changing water regimes and water quality management. Their applied research and extension experiences, particularly in areas with ecological similarities to the South Caucasus, enriched the analytical depth of the paper.

Sources were selected based on relevance, policy significance and applicability to low and middle-income country settings. The review prioritized materials published between 2015 and 2024, reflecting both the latest scientific consensus and post-pandemic development shifts. The analytical approach involved triangulating key findings, categorizing recommendations and cross-cutting themes. By integrating academic expertise with policy-oriented literature, this study offers a comprehensive, evidence-based framework for advancing climate-resilient and investment-ready fisheries and aquaculture systems, with a focus on vulnerable and transitional regions.

Analysis and Discussion

1. Climate Change and Aquatic Systems

The impacts of climate change are increasingly visible: rising atmospheric and ocean temperatures, retreating glaciers and higher sea levels. These shifts are driven by a sharp rise in greenhouse gases - carbon dioxide, which has increased by about 40% since the pre-industrial era, largely due to fossil fuel use and land-use changes. Aquatic systems, vital for fisheries and aquaculture, are profoundly affected. Oceans have absorbed around 93% of the excess heat and nearly a third of anthropogenic CO_2. These processes alter not only temperature but also ocean chemistry and circulation, disrupting ecosystems.

Both inland and marine aquatic systems face serious threats. Warmer temperatures, changing hydrology and ecological imbalances jeopardize fish stocks, biodiversity and livelihoods, especially in vulnerable regions. Changing rainfall patterns and melting glaciers further disrupt freshwater flows. In some areas, rain is becoming more erratic; in others, extended droughts reduce water availability. These shifts affect water quality, fish reproduction timing, and habitat availability. At sea, ocean currents like the Gulf Stream show signs of weakening, while upwelling systems may intensify, altering nutrient distribution and fish population dynamics. One of the more insidious consequences is ocean acidification. As CO_2 dissolves in seawater, it lowers pH levels, making oceans roughly 26% more acidic since the Industrial Revolution. This threatens shell-forming organisms like mollusks and plankton, which are crucial to marine food webs and coastal economies.

Climate models predict that these disruptions will persist for centuries, even if emissions were halted today. Marine primary production is expected to decline and freshwater systems will face mounting stress. Both are sensitive to light, temperature and nutrient changes, all exacerbated by climate shifts. Climate change is transforming not just the physical and chemical characteristics of aquatic environments but also the ecosystems they support. These realities demand more informed strategies, adaptive responses and sustainable investments to safeguard aquatic resources and the communities that rely on them.

2. Key Climate-Induced Impacts on Fisheries

Rising Temperatures and Thermal Stress:

As global temperatures rise, the consequences for wild and farmed fish species are evident. Warmer waters disrupt migration and spawning patterns and shift species' habitat ranges. Cold-water species like trout, common in freshwater systems, are particularly vulnerable. As oxygen levels decrease, these fish struggle to survive, leading to population declines. In the Black Sea, warming may cause anchovy and sprat to change migration routes or appear unpredictably, complicating fishing efforts and creating economic uncertainty for coastal communities.

Disease Outbreaks and Parasites:

Elevated water temperatures not only stress fish but also create ideal conditions for disease and parasite outbreaks. Aquaculture systems, where fish are raised in dense populations, are especially at risk. Warmer conditions weaken immune systems and accelerate infection spread, threatening both productivity and profitability. In natural waters, wild populations face increased pathogen exposure, complicating conservation and fishery management.

Shifting Rainfall Patterns and Water Systems:

Changing rainfall, snowmelt and seasonal water flows are reshaping aquatic ecosystems. Rivers may flood more intensely or dry up sooner, while lakes and reservoirs experience fluctuations that affect water quality and nutrient dynamics. These disruptions degrade fish habitats and reduce juvenile survival rates. In regions like the Black Sea basin, changes in freshwater inflow and salinity are affecting spawning areas, weakening fish stocks and reducing marine productivity.

More Frequent Extreme Weather Events:

Storms, floods, droughts and heatwaves are becoming more frequent and severe. These extreme events can damage aquaculture infrastructure, destroy fishing ports and erode critical habitats. Stronger storms and rising sea levels are accelerating coastal erosion and ecosystem damage.

Localized Acidification and Marine Impacts:

Though often viewed as a global issue, acidification is also affecting semi-enclosed seas like the Black Sea. Runoff and pollution add carbon, lowering pH and increasing acidity in localized areas. This poses risks to shell-forming species and food web stability, although the full impacts remain under investigation. Over time, this could reshape marine biodiversity and species’ availability.

3. Inland and Marine Fisheries in the Black Sea Basin

The Black Sea region faces a unique blend of pressures from both human activities and climate-related stressors. Inland fisheries are also increasingly under strain. These ecosystems support diverse, multi-species fisheries, typically sustained by small-scale fleets. Yet, across both marine and inland systems, shared challenges are mounting. Decades of overfishing, pollution and habitat degradation have already compromised ecological resilience. Now, climate change, manifesting through rising temperatures, sea level rise, and more frequent extreme weather events, is intensifying these vulnerabilities. Small pelagic species such as anchovy are already displaying shifts in migration and spawning behavior. Altered thermohaline structures, lower primary productivity in the southern basin, and disrupted seasonal cues are impacting their overwintering and schooling patterns. These ecological shifts directly threaten the livelihoods of fishing communities across bordering countries.

Freshwater systems face parallel threats. Upland and riverine environments are experiencing water scarcity, temperature extremes and declining biodiversity. Reduced river runoff and changing seasonal flows undermine the delicate balance of these ecosystems and disrupt traditional aquaculture practices. Climate-induced changes in fish behavior, habitats and species composition are reshaping freshwater communities. In the Mediterranean, this process has resulted in the "meridionalization" and "tropicalization" of fish species. The Black Sea is witnessing a comparable trend, known as "Mediterranization," where Mediterranean species are gradually expanding northward. While these changes introduce new ecological risks, they may also offer economic opportunities, particularly for small-scale fisheries. However, the capacity of these small-scale operations to adapt remains limited, especially in developing regions. Exposure to climate risks is often high, while institutional support, financial resources and access to scientific knowledge are frequently lacking. Countries across the Mediterranean and Black Sea regions differ significantly in their vulnerability. Generally, northern states benefit from stronger infrastructure and resilience, while southern and southeastern nations face greater exposure and fewer coping mechanisms. Although the Black Sea region’s national economies are less reliant on fisheries compared to other areas, socio-economic uncertainties and governance challenges continue to hinder effective resource management.

4. Adaptation and Mitigation Options

Resilience to climate change cannot be achieved through a universal solution; it requires context-specific strategies that blend scientific knowledge with local expertise and are shaped by inclusive engagement with communities and stakeholders. As global temperatures are projected to rise, the stakes become even higher: at 1.5°C of warming, risks to human health, food and water security, livelihoods and economic stability increase significantly, and grow more severe at 2°C. In this setting, adaptation and mitigation must function not as separate responses, but as complementary efforts, protecting the most vulnerable while exploring new opportunities that may arise from shifting ecosystems. For aquaculture-dependent communities, several practical adaptation strategies have proven both feasible and effective:

a) Species diversification: Introducing or breeding fish strains that are more tolerant of elevated temperatures and altered aquatic environments can reduce vulnerability to climate shocks.
b) Water management: The use of climate-resilient, low-water technologies such as recirculating aquaculture systems (RAS) helps optimize water use and reduce environmental impacts.
c) Ecosystem-based adaptation: Restoring wetlands, riparian zones and marine protected areas can strengthen natural buffers against climate impacts while supporting biodiversity.
d) Early warning systems: Implementing monitoring tools for extreme weather events and disease outbreaks can enable proactive responses, minimizing losses and disruptions.
e) Governance reform: Updating fisheries management frameworks to incorporate climate risk, while fostering regional cooperation, especially in ecologically sensitive areas like the Black Sea - is essential for long-term sustainability.

Mitigation also plays a critical role, particularly in reducing aquaculture's contribution to greenhouse gas (GHG) emissions. Shifting to renewable energy sources such as solar power, adopting efficient feeding strategies, improving waste management and reducing reliance on carbon-intensive inputs like fishmeal are central to this goal. Given that feed production is one of the largest sources of emissions in aquaculture, innovations such as sinking feeds and alternative protein sources can significantly lower environmental footprints. While mitigation is a global, long-term endeavor, its full benefits likely unfolding over decades, adaptation offers immediate, locally grounded solutions. Strengthening adaptive capacity, especially in developing regions, is key. These culturally rooted, time-tested practices can help communities better anticipate and respond to environmental change, making adaptation more inclusive and sustainable.

5. Sustainable Investment Pathways in Fisheries and Aquaculture

As aquatic ecosystems face increasing pressure from climate change, overfishing and pollution, sustainable investment in fisheries and aquaculture is essential. These sectors are vital to food security, livelihoods and the emerging blue economy, especially in vulnerable regions. When guided by strong legal frameworks and inclusive planning, climate-aligned investments can safeguard biodiversity, enhance economic resilience, and accelerate progress toward Sustainable Development Goal 14: Life Below Water. To support this transformation, investments should focus on the following interconnected areas:

5.1 Green Infrastructure and Innovation

Investing in technologies such as recirculating aquaculture systems, adaptive hatcheries and improved pond designs can raise productivity while reducing environmental impact. In flood or salinity-prone areas, green infrastructure also plays a crucial role in restoring habitats and improving water quality, offering both climate resilience and ecological benefits.

5.2 Cold Chains for Resilience and Market Access

A large share of post-harvest losses can be avoided through efficient cold storage and processing systems. Investing in climate-resilient cold chains not only preserves product quality and food safety but also helps stabilize incomes and ensure market continuity during climate disruptions.

5.3 Research, Extension and Knowledge Sharing

Climate adaptation starts with access to relevant knowledge. Strengthening local research capacity on species vulnerability and sustainable practices, along with delivering this knowledge through responsive extension services and digital tools, enables producers to make informed decisions.

5.4 Financial Risk Management and Insurance

Small-scale fishers and farmers are particularly exposed to climate-related risks. Affordable insurance products, financial safety nets and blended financing models can help de-risk investments and protect livelihoods, especially in the face of disease outbreaks or extreme weather.

5.5 Public-Private Partnerships for Inclusive Growth

Scalable impact requires collaboration. Well-structured public-private partnerships (PPPs) can unlock capital, share risks and ensure local voices, especially those of Indigenous peoples, women

and marginalized groups are included in decision-making. When designed with equity in mind, PPPs become a vehicle for innovation and long-term sustainability.

To ensure investments deliver lasting benefits, governments must establish clear climate safeguards, facilitate inclusive consultations and monitor environmental and social impacts throughout a project's lifecycle. Investment models should reflect local realities. Blended models that combine public oversight with private innovation and community ownership are often the most adaptive. Investing in fisheries and aquaculture is not only about economic return, it's about building a climate-resilient future. When thoughtfully designed, these investments can regenerate ecosystems, support vulnerable communities and transform the sector into a cornerstone of sustainable development. Regions like the Black Sea stand to benefit greatly from this integrated, forward-looking approach.

Conclusion

As climate change continues to intensify stress on aquatic systems, it is no longer sufficient to address fisheries and aquaculture challenges in isolation. Instead, a dual approach that prioritizes both adaptation and mitigation, grounded in local realities and supported by strategic investments, must guide the future of these sectors. This analysis demonstrates that climate-resilient aquaculture is not only feasible but necessary, particularly in vulnerable regions such as the Black Sea basin.

Adaptation strategies, including species diversification, ecosystem-based restoration and climate-smart technologies, offer communities tangible tools to respond to increasingly unpredictable environmental conditions. However, adaptation cannot operate in a vacuum. It must be supported by robust investments that prioritize low-emission infrastructure, inclusive public-private partnerships and innovations in knowledge transfer and financial risk management. Equally vital is the integration of traditional knowledge and community participation, which enhances both the relevance and effectiveness of these solutions.

Legal and policy frameworks, informed by science and grounded in equity, play a catalytic role in enabling sustainable transformation. The active engagement of universities provides valuable applied research and training that support capacity building in rural and climate-sensitive areas. A climate-aligned investment paradigm must recognize the fisheries and aquaculture sectors not only as contributors to national economies and food systems but as key drivers of biodiversity protection, social inclusion and ecological regeneration. With intentional design, targeted funding and cross-sector collaboration, these sectors can lead the shift toward a blue economy that is both resilient and regenerative. The success of climate-resilient aquaculture will depend on how well we connect science, policy and practice - anchored by local ownership and global solidarity.

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