Postprint: Genomic Perspectives on Adaptive Strategies of Marine Fishery Organisms to Environmental Stress

Authors: Li Li, Zhang Guofan

Date: 2016-12-26T00:00:00+00:00

Abstract

Marine fisheries (including capture and aquaculture) provide protein that serves as an important source of animal protein in the global human diet, while also representing a vital source of livelihood for numerous countries. China is a major marine fisheries nation, and ensuring the sustainable development of marine fisheries is of great significance for safeguarding national food and nutritional security. Coastal ecosystems are the most productive regions for marine fisheries output. Against the backdrop of global warming, factors such as coastal overexploitation, habitat destruction, and land-based pollution subject China' s fishery organisms to persistently high-stress environments, thereby posing substantial challenges to the sustainable development of marine capture fisheries and mariculture. Advances in genomics and related disciplines have rendered possible the precise assessment and prediction of adaptation potential in marine organisms under high-stress conditions. This article reviews the current state of research on environmental stress adaptation in China' s fishery organisms, aiming to identify the key scientific questions in the study of environmental adaptation and evolution of marine fishery organisms, and further proposes recommendations for future research to promote the precise management of China' s marine fishery biological resources and aquaculture, as well as the healthy and sustainable development of the industry.

Full Text

Genomic Perspectives on Adaptive Strategies of Marine Fishery Organisms to Stressful Environments

Li Li, Zhang Guofan*

Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

*Corresponding author

Abstract

Marine fisheries (including capture and aquaculture) provide crucial animal protein sources for global human diets and represent a critical livelihood for numerous nations. As a major marine fishery country, ensuring the sustainable development of marine fisheries is vital for safeguarding China' s food and nutrition security. Coastal ecosystems are the most productive regions for marine fisheries. Against the backdrop of global warming, overexploitation, habitat destruction, and land-based pollution have exposed China' s fishery organisms to persistently high-stress environments, posing enormous challenges to the sustainable development of both marine capture fisheries and mariculture. Advances in genomics and related disciplines have made it possible to precisely assess and predict the adaptive potential of marine organisms under high-stress conditions. This article reviews the current status of research on stress adaptation in China' s fishery organisms, aiming to identify the key scientific questions in marine fishery environmental adaptation and evolution research, and further proposes future research directions to promote precision management of marine fishery biological resources and aquaculture, as well as the healthy and sustainable development of the industry.

Keywords: genome, fishery organisms, environmental stress, adaptation strategies, scientific issues, intensive management

DOI: 10.16418/j.issn.1000-3045.2016.12.009

1. Impacts of Environmental Stress on Marine Fishery Organisms

Marine fisheries (including capture and aquaculture) provide important animal protein sources for global human diets and represent a critical livelihood source for numerous countries [1]. In today' s world, environmental changes caused by direct and indirect human activities have profoundly impacted Earth' s life systems and agriculture. Global climate change has induced extensive physical and chemical alterations in the ocean, including uneven warming of seawater temperature, ocean acidification, decreased surface water density, and changes in ocean circulation and upwelling, all of which significantly affect marine ecosystems and fishery organisms. China' s coastal environment and ecology are influenced not only by global climate change phenomena such as oceanic and monsoonal effects but also face multiple stressors including overexploitation, habitat destruction, and environmental pollution, resulting in unprecedented changes in coastal ecosystems [2,3]. For instance, the 2015 *China Marine Environmental Status Bulletin* revealed severe pollution in China' s coastal waters, with 86% of monitored estuarine, bay, and coral reef ecosystems in sub-healthy or unhealthy conditions. Oyster reef ecosystems in major estuarine areas have been almost completely destroyed, while harmful algal blooms and green tides show increasing trends in affected area. Coastal reclamation and arbitrary alteration of natural shorelines frequently destroy fishery organism habitats. In some coastal areas of the Bohai Sea, Yellow Sea, and East China Sea, seawater intrusion and soil salinization are worsening, and erosion of sandy and silty coasts is prominent. Shellfish toxins and heavy metals that seriously affect human health are widespread in the environment and fishery organisms. In summary, China' s coastal seas are in a critical situation with strong complexity due to the combined effects and cumulative impacts of climate change and human activities.

As a major producer and consumer of marine aquatic products, research on the adaptation strategies of marine fishery organisms to stressful environments is crucial for ensuring the sustainable development of China' s marine fisheries and safeguarding national food and nutrition security. This article will review the domestic and international research status on marine environmental changes and environmental stress on marine fisheries from a genomic perspective, discuss the coping strategies of marine fishery organisms, and propose recommendations for further research in related fields.

Countries such as the United States, United Kingdom, France, and Canada attach great importance to research on the adaptation of marine fishery organisms and the formulation of response strategies under global change. The Food and Agriculture Organization (FAO) released a technical report on fisheries resources and aquaculture in response to global change as early as 2009 [4], systematically explaining from environmental, economic, and social perspectives how global change affects the world' s fisheries sector. The 21st Conference of the Parties to the United Nations Framework Convention on Climate Change was held in Paris in December 2015, resulting in the signing of the Paris Agreement. The agreement aims to strengthen efforts to address the global threat of climate change in the context of sustainable development and poverty eradication. The conference explicitly highlighted the role of oceans in temperature regulation and carbon sequestration while emphasizing the urgency of reversing current trends of overexploitation and pollution to restore the productivity functions of marine ecosystem services [1]. In May 2016, a review report completed by 14 international marine science experts, *The Future of the Ocean: An Independent Scientific Overview of Marine Research Issues of Interest to the G7 Nations*, analyzed and evaluated important marine research issues of global concern. Among the eight issues listed, ocean warming, acidification, biodiversity loss, and marine ecosystem degradation were identified as major problems in today' s marine domain [5].

Undoubtedly, a good aquaculture system depends on suitable cultivation environments. Most mariculture organisms are distributed in environmentally sensitive coastal zones or estuarine areas, making them more vulnerable to environmental changes. Moreover, compared with free-moving marine organisms in natural wild states, cultured organisms are more dependent on the environmental conditions of the cultivation area. Unsuitable cultivation environments can affect the growth, reproduction, and development of cultured organisms, thereby influencing aquaculture production and efficiency. Environmental changes, especially sudden environmental shifts, can also cause large-scale mortality of cultured organisms (Figure 1 [Figure 1: see original paper]). Particularly when cultured organisms reach certain densities in cultivation areas, mass mortality events are prone to occur (e.g., in bivalves and crustaceans), representing a widespread problem in aquaculture industries in China and worldwide. The causes of such mass mortality in aquatic animals remain unclear, with research suggesting they result from the combined effects of hosts, pathogens, and cultivation environments [12]. Both pathogens and environmental stressors such as temperature, salinity, food scarcity, hypoxia, pollution, and unreasonable cultivation models are potential contributing factors [13,14]. Global warming-induced deterioration of cultivation environments also alters the distribution and pathogenicity of pathogenic organisms; for example, environmental stressors like temperature and salinity have been reported as inducing factors for disease outbreaks in cultured animals [15]. In summary, the causes and mechanisms of mass mortality events resulting from comprehensive environmental deterioration have long been a focus and challenge for the global aquaculture industry.

2. Basic Research on Marine Fishery Organisms' Responses to Environmental Stress

Wild fishery resource conservation and aquaculture are closely connected and inseparable in addressing environmental stress. Wild fishery resource protection provides more germplasm resources for aquaculture, while aquaculture can reduce dependence on wild resources [16,17] and better meet human food and nutrition needs, particularly for high-nutrition foods. This deeply reflects that rational protection and effective utilization of marine resources are two core elements for the sustainable development of China' s marine fisheries, requiring balanced development. However, research on the sustainable development of marine fishery resources and aquaculture has different connotations and focuses. The former emphasizes the dynamic evolution of natural resources and biodiversity conservation, while the latter is primarily an agricultural issue focusing on the physiological and ecological adaptation of cultured organisms. Studying the impacts of environmental changes on marine fishery resources and cultured organisms ultimately concerns the short-term responses and long-term adaptation of marine fishery organisms to environmental changes. Given that wild resources and cultured populations constitute the main components of coastal ecosystem communities, their distribution and composition are important indicators of ecosystem health. This article focuses on the individual and population levels of marine fishery organisms.

At the individual level, organisms exhibit three types of responses to environmental changes: (1) escaping to more suitable environments; (2) adjusting their physiological and biochemical states through phenotypic plasticity to adapt to changing environments; and (3) dying due to inability to adapt to new environments, thereby altering population genetic structure. These three responses reflect different adaptation strategies and varying degrees of environmental impact. From an environmental adaptation perspective, aquaculture concerns not only genetic factors but also ecological responses such as physiological plasticity, while fishery resource management focuses more on genetic and evolutionary responses to environmental change.

In recent years, the rise of genomics has opened a door to understanding the world at microscopic scales. As a discipline following synthetic and molecular biology, genomics has revolutionized life sciences. The integration of genomics with ecology and aquaculture has endowed new research connotations for the ecological adaptation management of marine fishery organisms. As omics research advances to the levels of populations, individuals, and even genes, researchers can more precisely evaluate the impacts of environmental stress on fishery organisms and more accurately predict their adaptive potential. The genome, as the sum of all genetic material, is the source of hereditary variation; simultaneously, spatiotemporal changes in genome structure and function are the primary outcomes of life' s adaptive evolution. Genome structure and function are important contents of life sciences and key means for understanding life processes. Genomics offers tremendous advantages for studying physiological, genetic, and evolutionary responses of marine fishery organisms to environmental stress at different spatiotemporal scales.

2.1. Physiological Responses and Genetic Mechanisms of Cultured Organisms to Environmental Change

China' s mariculture is mostly located in intertidal zones, inner bays, estuaries, or coastal waters, making it particularly vulnerable to direct or indirect human activities, and environmental deterioration in cultivation areas is an undeniable reality. Factors determining the stress tolerance of cultured organisms include not only the genetic composition of cultured populations but also their physiological plasticity in response to environmental changes. Analyzing the response mechanisms of cultured organisms to environmental changes from molecular, physiological, individual, and population levels represents the overall development trend in this research field, and the development of various omics technologies has significantly advanced in-depth analysis of these response mechanisms.

First, research should focus on key environmental factors. Targeted studies should be conducted under the background of global warming, addressing China' s actual environmental and cultivation conditions. We identify five aspects of environmental change driven by global change that require particular attention: (i) **Temperature**. The most important changes to marine physicochemical environments caused by global change are warming and acidification. Temperature is the most critical environmental factor affecting organisms, directly or indirectly influencing physiological and metabolic processes. As poikilotherms, marine animals are particularly sensitive to environmental changes, and extreme temperature variations are a major cause of large-scale mortality in China' s aquaculture. (ii) **Acidification**. After ocean warming, acidification is the most significant environmental change factor in the ocean, affecting the mineralization processes of coral resources and related organisms such as shellfish and crustaceans, and represents a hotspot in international marine global change research. (iii) **Hypoxia or anoxia**. Global change and land-based pollution can cause hypoxia or anoxia in local sea areas, which has also been confirmed as one of the important stress factors causing large-scale aquaculture mortality in recent years. (iv) **Food scarcity**. Food scarcity is an important indirect impact on cultured organisms resulting from temperature-driven environmental changes. Algae are also the primary productivity for energy transfer in aquaculture ecosystems and are crucial for maintaining system stability. (v) **Heavy metals and shellfish toxins**. Both are important environmental pollution factors in China, exhibit cumulative effects in aquatic animals, and are closely related to the safety of marine aquatic products and human health.

Second, research should investigate physiological responses and genetic mechanisms targeting these stress factors through three approaches: (i) **Genetic and molecular mechanisms**. This involves analyzing the mechanisms of important physiological, biochemical, and metabolic processes during stress response, identifying key genes and highly adaptive genotypes. Particular emphasis should be placed on parsing unique and shared response mechanisms to different stress factors and their interactions. (ii) **Physiological plasticity**. This focuses on studying the impacts of important aquaculture physiological processes on growth, development, and survival under different stress conditions, identifying physiological critical points under varying stress levels and the physiological capacity of cultured organisms. (iii) **Prediction of mass mortality events and molecular pathways for breeding stress-adapted strains**.

Third, research on stress response mechanisms in aquatic organisms shows a trend toward multi-level investigation: (i) **Molecular level**. This is a crucial means for studying the genetic and plasticity mechanisms of adaptation. (ii) **Physiological and biochemical level**. Physiological and biochemical stress responses in aquatic organisms are important for studying their physiological capacity. For example, energy metabolism balance is a key physiological indicator reflecting stress levels at the individual level, establishing linkages between different stress factors to reflect organismal stress [18]. (iii) **Individual and ecological levels**. Impacts at individual and ecological levels directly relate to aquaculture production and mass mortality.

Finally, methodological exploration should include three aspects: (i) **Molecular techniques**. Current molecular-level detection can cover genome sequences, structures, transcriptional regulation, translational regulation, post-translational modification, and epigenetic modifications. (ii) **Omics**

technologies. The development of omics technologies has enabled various detections with greatly improved automation and throughput. Post-translational modifications and other epigenetic regulations are receiving increasing attention due to their important roles in rapid, short-term adaptation. (iii) **Physiological techniques**. Physiological-level research primarily involves establishing suitable physiological indicators for marine organisms, such as heart rate measurement and oxygen capacity determination.

In summary, omics approaches are effective pathways for parsing specific mechanisms of different stress factors and their synergistic effects, particularly in identifying the main driving factors of mass mortality. Physiological-level research integrates stress factors formed by different stressors to investigate response mechanisms at individual and ecological levels.

2.2. Precision Genetic Assessment of Fishery Resources

First, it is essential to **identify evolutionary driving factors and investigate adaptive divergence**. Biodiversity at species and population levels results from the combined effects of mutation, drift, gene flow, and environment, plus human impacts such as inbreeding in aquaculture affecting wild population structures. Distinguishing genetic differentiation caused by various evolutionary drivers is crucial for fishery resource management. Traditional resource management and conservation research mostly ignored environmental selection, using only neutral markers for phylogeographic analysis to study geographic structure and genetic differentiation caused by reproductive isolation among intraspecific groups. Recent discoveries reveal that environmental heterogeneity in marine organisms exceeds previous understanding, with adaptive differentiation caused by natural environmental selection pressure being widespread. Genetic management models based solely on neutral drift can no longer meet the needs of modern fine-scale fishery resource management [19]. For example, increasing evidence shows widespread local adaptation in marine organisms, with some populations differentiating within just a few kilometers or even meters [20]. Local adaptation results from the balance between gene flow and natural selection. Research on adaptive differentiation and its mechanisms in fishery organisms is an important component of studying environmental change impacts on marine life and is significant for achieving precise management of marine ecosystems. However, determining evolutionary driving factors, particularly the mechanisms of adaptive differentiation, has long been challenging.

Second, **evolutionary responses of fishery organisms to stressful environments** represent a hotspot in fishery resource conservation research, encompassing three aspects: (i) Conducting population-level diversity assessments for species with important economic and ecological value and well-preserved natural resources in China, distinguishing genetic differentiation caused by various evolutionary drivers (genetic drift, gene flow, environmental variation, aquaculture inbreeding). (ii) Investigating environmental adaptation mechanisms of organisms in different intertidal zones. The intertidal zone is a region of high temporal and spatial variability in marine environments, where typical marine environmental factors such as temperature and salinity change dramatically, and organisms are rhythmically exposed to air. Environmental factors in intertidal zones show mosaic distribution patterns with high overall heterogeneity, making it an excellent system for studying marine environmental adaptation. (iii) Studying adaptive differentiation at microevolutionary scales using different ecotype populations or closely related species. Microevolution is the source of biological variation and the foundation for environmental adaptation, remaining a hotspot in life sciences research. Microevolution studies focus on gene selection for traits and the effects of selection on genetic variation, serving as an important means to investigate fishery resource evolutionary responses to stressful environments.

Third, **research methods for adaptive differentiation** essentially examine genetic composition changes in natural populations under different environments or at different stages of environmental change. Phenotypic changes caused by environmental variation are necessary but insufficient conditions for identifying adaptive traits in populations. Adaptive differentiation components in genetic differentiation can be determined through: (i) **Reciprocal transplant experiments**, where organisms from different sources are cultivated in each other' s native environments to observe whether different populations show significant fitness advantages in their home environments; (ii) **Studying gene frequency changes across different spatiotemporal scales**; and (iii) **Model predictions**, using the principle that differentiation in quantitative traits (QST) among populations is greater than that at neutral loci, or by screening for outlier loci from neutral markers to identify selected loci.

Fourth, **advancing precision research on genetic resource evolution mechanisms through genomics**. Continuous development in genomics has enabled studying spatiotemporal evolution of natural population structure and function at the omics level. For example, genome scanning using next-generation sequencing allows genetic variation detection at the resolution of single individuals and single nucleotides, with throughput increasing from single loci to tens of thousands of markers. The increased throughput not only avoids inconsistencies in population structure identification caused by small numbers of markers but, more importantly, enhances statistical power, ensuring accurate identification of a small number of adaptive loci. Additionally, with completed whole-genome information, functional information for these adaptive loci can be obtained [21].

3. Summary and Recommendations

Human activities, both direct and indirect, have significantly impacted fishery resources and aquaculture environments. There is an urgent need to formulate corresponding response strategies, strengthen precision management of China' s fishery resources, enhance basic research on aquatic organism responses to environmental change, and achieve sustainable development of fishery resource management and aquaculture—important guarantees for the healthy development of China' s "Blue Granary." This requires interdisciplinary integration, systematic data collection across broad spatiotemporal scales, and strengthened application of big-data approaches such as genomics.

First, **cross-disciplinary integration** is essential. Precision management of fishery resources and healthy development of aquaculture organisms are interdependent, making integration between these two fields crucial. On one hand, management of natural resources for economically important cultured organisms should be strengthened to ensure germplasm diversity. On the other hand, aquaculture research should be integrated with China' s actual ecological and environmental conditions. Regarding responses to environmental change, research on phenotypic plasticity and ecological response mechanisms should be enhanced, utilizing natural resource variation in cultured organisms for adaptation mechanism studies while emphasizing the integration of new genomic technologies with traditional disciplines (e.g., ecological genomics).

Second, **long-term data surveys** should be conducted. Key fishery areas with important economic and ecological value and abundant wild resources should receive priority protection, with strengthened basic research for precision resource management and establishment of genetic management regulations for important cultured organisms. Investment in aquaculture environmental monitoring should be increased to establish scientific health platforms for cultured organisms, enabling long-term tracking and investigation of mass mortality events. Both resource surveys and long-term systematic monitoring of environmental parameters require strengthening.

Third, **enhance capacity building for genomics big-data application**. While strengthening omics research, greater efforts should be made in constructing omics technology platforms and talent cultivation. Integration of genetic resource information across different species should be achieved by establishing genomic databases for important fishery and aquaculture organisms.

Acknowledgments

Academician Tang Qisheng provided valuable comments and suggestions for this article, for which we are deeply grateful.

References

[1] Food and Agriculture Organization. The state of world fisheries and aquaculture 2016. http://www.fao.org/3/a-i5555e.pdf.

[2] Lü Y L, Yuan J J, Li Q F, et al. Impacts of land-based human activities on coastal ecosystems. *Acta Ecologica Sinica*, 2016, 36(5): 1183-1191.

[3] Cai R S, Qi Q H. Climate change and global oceans: Interpretation of impacts, adaptation, and vulnerability assessment. *Climate Change Research*, 2014, 10(3): 185-190.

[4] Food and Agriculture Organization. Climate change implications for fisheries and aquaculture. http://www.fao.org/docrep/012/i0994e/i0994e00.htm

[5] Overview of new actions and commitments initiated by the G7 summit. [2016-07-01]. http://mp.weixin.qq.com/s?___{biz}=MzAwMzI3MDQ4OA==&mid=2650306163&idx=1&sn=da6e1

[6] Hutchings J A, Cote I M, Dodson J J, et al. Climate change, fisheries, and aquaculture: trends and consequences for Canadian marine biodiversity. *Environmental Reviews*, 2012, 20(4): 220-311.

[7] Callaway R, Shinn A P, Grenfell S E, et al. Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation-Marine and Freshwater Ecosystems*, 2012, 22(3): 389-421.

[8] Sun S, Sun X X. Changes in marine biological functional groups and ecosystem evolution. *Advances in Earth Science*, 2014, 29(7): 854-858.

[9] Sun S, Zhang Y S. Research progress on marine ecosystem dynamics and sustainable mechanisms. *Advances in Earth Science*, 2005, 20(12): 1280-1287.

[10] Tang Q S. Multi-trophic integrated aquaculture. *Progress in Fishery Sciences*, 2013, 34(1): 1-11.

[11] Sun S, Sun X X. Changes in marine biological functional groups and ecosystem evolution. *Advances in Earth Science*, 2014, 29(7): 854-858.

[12] Samain J F. Review and perspectives of physiological mechanisms underlying genetically-based resistance of the Pacific oyster *Crassostrea gigas* to summer mortality. *Aquatic Living Resources*, 2011, 24(3): 227-236.

[13] Davies C E, Johnson A, Wootton E C, et al. Effects of population density and body size on disease ecology of the European lobster in a temperate marine conservation zone. *Ices Journal of Marine Science*, 2015, 72(z1): 128-138.

[14] Lafferty K D, Harvell C D, Conrad J M, et al. Infectious diseases affect marine fisheries and aquaculture economics. *Annual Review of Marine Science*, 2015, 7: 471-496.

[15] Rowley A F, Cross M E, Culloty S C, et al. The potential impact of climate change on the infectious diseases of commercially important shellfish populations in the Irish Sea-a review. *Ices Journal of Marine Science*, 2014, 71(4): 741-759.

[16] Han D, Shan X, Zhang W, et al. A revisit to fishmeal usage and associated consequences in Chinese aquaculture. *Review of Aquaculture*, 2016-10-22, Online, http://onlinelibrary.wiley.com/doi/10.1111/raq.12183/full

[17] Shan X J, Han D, Zhang W B, et al. Chinese aquaculture alleviates pressure on wild fishery resources. *China Fisheries*, 2015, (6): 5-6.

[18] Sokolova I M, Frederich M, Bagwe R, et al. Energy homeostasis as an integrative tool for assessing limits of environmental stress tolerance in aquatic invertebrates. *Marine Environmental Research*, 2012, 79: 1-15.

[19] Conover D O, Clarke L M, Munch S B, et al. Spatial and temporal scales of adaptive divergence in marine fishes and the implications for conservation. *Journal of Fish Biology*, 2006, 69(c): 21-47.

[20] Sanford E, Kelly M W. Local adaptation in marine invertebrates. *Annual Review of Marine Science*, 2011, 3: 509-35.

[21] Stillman J H, Armstrong E. Genomics are transforming our understanding of responses to climate change. *Bioscience*, 2015, 65(3): 237-246.

Li Li is a research professor at the Institute of Oceanology, Chinese Academy of Sciences and Qingdao National Laboratory for Marine Science and Technology, and a key member of the International Oyster Genome Project. Her research interests focus on mollusk genetics, evolution, and breeding biotechnology. In recent years, she has been engaged in the protection and sustainable utilization of mollusk resources, specifically using genomic and molecular tools to study the molecular basis of economic and ecological traits, adaptive evolution, and molecular breeding in oysters and other shellfish.

E-mail: lili@qdio.ac.cn

Zhang Guofan is a senior research professor at the Institute of Oceanology, Chinese Academy of Sciences (IOCAS), serving as Chief Scientist of the IOCAS Academic Committee, Chief Scientist of the Shellfish Industrial Technology System of the China Agriculture Research System, and Director of the National & Local Engineering Laboratory for Ecological Mariculture. He previously served as Chief Scientist of the National Basic Research Program of China ("973" Project) "Molecular basis of key economic traits and molecular design breeding in cultural mollusks" and Chief Scientist of the International Oyster Genome Project (PAG). Dr. Zhang and his team focus on three main aspects of molluscan research: (1) genetics and breeding of shellfish, including hybridization, GWAS, and genomic selection breeding; (2) stress adaptation and evolution of shellfish, including phenotypic plasticity, gene regulation pathways, population genomics, and micro-evolution; and (3) shellfish cultural technology improvement, especially healthy and sustainable mariculture based on ecological systems.

E-mail: gfzhang@qdio.ac.cn

Note: Figure translations are in progress. See original paper for figures.