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Evolutionary Adaptations of Deep-Sea Creatures: Climate Change and Captive Fish Migration

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ABSTRACT

The deep sea, encompassing more than 60% of Earth's surface, constitutes one of the planet's harshest and least investigated ecosystems, inhabited by species with remarkable adaptations to high pressure, constant darkness, and limited supplies. These adaptations facilitate life in extreme environments but render deep-sea organisms particularly susceptible to the persistent effects of climate change and anthropogenic activities, such as deep-sea mining and bottom trawling. This review examines the evolutionary adaptations of deep-sea species and emphasizes their physiological, morphological, and behavioral mechanisms. It analyses the impact of climate change-related stressors, such as increasing ocean temperatures, acidification, and deoxygenation, on their survival and dispersal. Furthermore, it examines deep-sea fish's migration patterns and captive habits, emphasizing their ecological importance and conservation challenges. This study synthesizes findings from several studies to identify significant knowledge gaps, particularly concerning the long-term impacts of multiple stressors and the contribution of the deep sea to the global carbon cycle. Using an interdisciplinary approach, it proposes actionable recommendations for future research, including studies on physiological resilience and applying genomic technologies to explore adaptation mechanisms. These findings guide conservation initiatives, including establishing marine protected zones and enforcing international restrictions on deep-sea resource extraction. This study underscores the significance of conserving deep-sea biodiversity to sustain ecosystem integrity and global climate equilibrium. It establishes a basis for enhancing research and policy in this vital domain.

INTRODUCTION

Evolutionary adaptation of deep-sea creatures is one of the great inspirations of marine biology, and the study of those deep-sea animals gives us solid information about the processes of evolution and adaptability. Covering more than 60% of the surface of Earth, the deep sea is among the harshest environments on the planet and is characterized by high hydrostatic pressure, low temperatures, and complete darkness. The extreme nature of these environments has led to unique physiological, morphological and/or behavioral adaptations, allowing life to occupy previously too extreme to be habitable environments. Significance of deep sea; it plays a critical role in regulating global climate systems, acts as a carbon sink, and a major species reservoir (Petitjean et al., 2021). Climate change impacts, such as temperature, acidification, oxygen depletion, and the anthropogenic drivers of global environmental change (Hittle et al., 2021). Recent studies show that global ocean warming has reached its highest level, and deep-sea ecosystems are experiencing measurable thermal changes, disrupting the ecological balance. Advances in ROVs and eDNA analyses notwithstanding, predicting the consequences of climate change and human impacts on deep-sea biodiversity and ecological services is still fraught with uncertainty. The goal of this review is to summarize the current knowledge on the evolutionary modifications deep-sea organisms have evolved. Addressing at climate change and the migratory effect of captive fish on these unique ecosystems (Ham and Shon, 2020).

Recent studies have explored various aspects of deep-sea biology: the biochemical processes that allow organisms survive under high pressure, the role of deep sea animals in the nutrient cycle and in the sequestration of carbon, among others. Studies on piezolytes, notorious compounds inside pressure-resistant deep-sea animals, have displayed their crucial role in proteostasis through a vital stabilization of proteins at high hydrostatic pressure (Takeuchi et al., 2020). Bioluminescence has also been extensively investigated in the context of predation, communication, and camouflage within palettes of low light environments where this seem to be crucial adaptations. Despite these advances, there remain significant knowledge gaps in long-term impacts of climate change on deep-sea taxa. The combined effects of higher temperatures, acidification and deoxygenation on physiological and ecological processes remain extremely rare (Frühauf et al., 2020). Furthermore, little is known about depth-migratory responses to environmental stressors for deep-sea fish, as the vast majority of research has been with shallow-water species (Hittle et al., 2021). These gaps have hindered efforts to predict the cascading effect of global environmental change on biodiversity and ecosystem stability. Even so, these issues must be addressed to improve our knowledge on the resilience of deep-sea ecosystems and provide guidance for conservation policies as the pressures of anthropogenic stressors continue to rise on these largely unexplored ecosystems (Frühauf et al., 2020).

The present review tried to bridge these gaps by presenting current information about the physiologic evolution of deep sea organisms and the role of climate change and the anthropogenic fish transfer on these systems (Tabari et al., 2020). The integration of information from physiology, ecology and conservation biology to create frameworks for a better understanding of the topic in one review is an innovative approach (Barrouin-Melo et al., 2016). Compared to earlier studies focusing on individual components of deep-sea life, this review explores the relationship between evolutionary modifications, ecological challenges, and human impacts. It attempts to close the gap between theory and practical application and hence, offers ramifications for the future of deep-sea science and conservation. The data presented here may influence policy, while informing marine protected area (M MPA) design, and restricting industrial activities, as well as future climate adaptation and biodiversity [14] conservation research (Castillo et al., 2018). This review will improve the academic understanding of deep-sea ecosystems and highlight its importance in supporting global environmental health (Kang et al., 2020).

Physiological and Morphological Adaptations of Deep-Sea Creatures

Deep-sea ecosystems are amongst the most extreme environments on the planet where high hydrostatic pressure, perpetual darkness, and limited food resources prevail **(Fig. 1)**. Those organisms which thrive here, possess a wide array of physiological and morphological modifications to withstand the conditions of stress. Understanding these modifications highlights the tenacity of life, also helps us to understand and anticipate responses of these taxes to environmental changes, such as climate change and human induced disturbances (Weber et al., 2020).

Mechanisms for Tolerance to Extreme Pressure and Temperature

One of the most challenging environmental tolerances that deep-sea species have to contend with is the high hydrostatic pressure, which increases approximately 1 atm per 10 m of depth. Below 1,000 meters deep, pressure can occur at more than 100 MPa (Mu et al., 2018), which is a substantial mechanical and biochemical challenge for various cellular and molecular processes (Mu et al., 2018). They have pressure-resistant proteins and membranes adapted to the pressures at these depths. Trimethylamine N-oxide (TMAO) is a small organic compound that acts as a piezo Lyte, a class of substances that stabilizes proteins and preserves their activity under high pressure. In fish (like that of grenadiers and snailfish), TMAO level increases with depth, which tracks their physiological ability to live at the greatest depths, possibly meaning that each release has begun to threat the calcium carbonate balance of the entire ocean, one peak at a time (Freed et al., 2019).

Temperature is a fundamental environmental variable in the deep-sea. In such locations, the temperature has the potential to drop below 4°C requiring the organism to undergo metabolic modification to survive. Cold-adapted enzymes in deep-sea species support their catalytic activity at lower temperatures (Tsutsui et al., 2016). Offset the lower vibrational energy at these temperatures. These enzymes are structurally plastic. Moreover, cellular membranes undergo structural changes to maintain fluidity at lower temperatures, typically through the inclusion of increased amounts of unsaturated fatty acids (Röthig et al., 2017).

Bioluminescence and Sensory Adaptations for Dimly Lit Environments

Since sunlight penetrates little more than 200 m, deep sea is permanently dark, highlighting bioluminescence — light emitted by organisms through chemical reactions — as an adaptation hallmark in the deep sea. Such skill performs several ecological roles including evading predators, attracting prey, and communication (Nakaya et al., 2016, Collins et al., 2021).

Apart from bioluminescence, the species are also specially adapted to diving deep by having specific sensory adaptations to be able to sense very faint light and vibrations. Many species, such as this barrel-eye fish, have exceptionally sensitive eyes for detecting bioluminescent signals or faint background light (Masanari et al., 2016). Their eyes have adapted with a larger lens and larger retina that are optimized for absorbing photons. In contrast, for species with no or limited visual ability — for example, deep-sea crabs, which can visually perceive only a few meters. Mechanoreception is used to detect water currents and chemical signals (Zeng et al., 2020).

Specialized Feeding Behaviors in Nutrient-Deficient Ecosystems

The scarcity of food in deeper waters requires specialized feeding strategies and metabolic coping strategies. Many deep-sea organisms have opportunistic feeding strategies, consuming everything that falls from the upper ocean layers — marine snow. These include the remains of organic particles, dead plankton, and fecal pellets (Cheng et al., 2019). Scavengers like hagfish and amphipods are phenomenally adapted for feeding on these occasional food supplies. They have elastic jaws and dilatable stomachs allowing them to swallow large quantities when food is available (Danovaro et al., 2020).

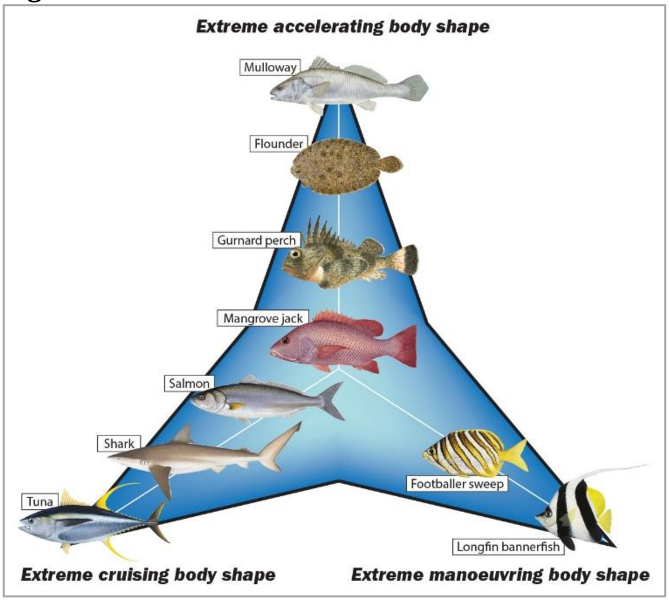
Also, some deep-sea creatures have developed predatory traits that have been finely tuned for maximal feeding efficiency. Alternatively, gulper eels are able to swallow prey massively larger than itself thanks to its wide jaws whilst species like the viperfish possess long, fang-like teeth to capture small, rapid prey in low-light environments (Crowe-Riddell et al., 2016). Other species, like giant tube worm, formed symbiotic relationships with inorganic molecule-chemosynthetic bacteria, in which the symbionts take inorganic energy sources, like hydrogen sulfide (Tortorella et al., 2018).

Distinct Reproductive Strategies in Secluded Ecosystems

The challenges of low population densities and limited access to mates are evident in the reproductive adaptations of deep-sea organisms. Many of the species are hermaphroditic, meaning that any individual can serve as a male or female during reproduction, increasing the likelihood of successful mating (Xie et al., 2018). Some among these deep-sea fish (e.g., tripod fish), are simultaneous hermaphrodites capable of self-fertilizing in the absence of a partner (Gan et al., 2020).

For organisms that have two sexes, we even have extremely specialized reproductive methods, such as male parasitism, where the male develops only to the point where he can inject sperm and then clings to the female. The anglerfish represents just such a remarkable case — in which the male fuses to the female, becoming so dependent on her for sustenance that he is capable only of delivering sperm, when needed. This ensures reproduction in an environment where mate finding could be particularly difficult (Isogai et al., 2018). Additionally, many deep-sea organisms produce many yolky eggs, providing sufficient energy for the longlasting larvae with free diffusion in nutrient-poor environments (de Busserolles and Marshall, 2017).

Figure 1

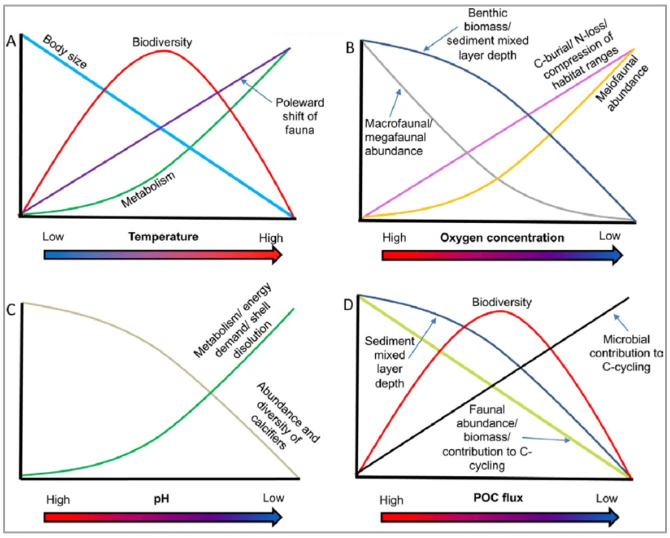


A triangular model conceptually dividing fish body shapes based on their adaptations to swimming behaviors. The top end of the spectrum is the "high accelerating body shape" which are high-powered species, such as Mulloway, Flounder and Gurnard perch, used for quick bursts of speed to pursue prey or evade predators. The extreme cruising body shape is represented in the bottom left corner and is characteristic of species such as Tuna, Sharks and Salmon, which are adapted for long-distance, low-cost swimming. In the bottom right corner, what is referred to as "extreme maneuvering body shape" is indicated—species such as the Footballer Sweep and Longfin Bannerfish with this body type are likely adapted for precise movements in complex habitats (such as coral reefs). This suggests that much of the evolution of body design has been a compromise between the competing forms of movement oriented towards the different ecological niches based on the three competing forms of locomotion speed, endurance, and agility.

Effects of Climate Change on Deep-Sea Ecosystems

Even with its isolation from the surface domains, deep water is not free from the widespread influences of climate change. The wide range of this mostly unexplored ecosystem faces many environmental changes due to climate change, such as high temperatures, ocean acidification, deoxygenation, and disruption of the biological pump (example depicted in **Figure 2)**. Such changes threaten the delicate balance of deep-sea ecosystems, which have evolved in stable conditions for millions of years (Danovaro et al., 2016).

Figure 2



The figure depicts the anticipated impacts of climate change on deep-sea benthic communities due to many environmental stresses. Panel A illustrates the correlation between temperature and biodiversity, metabolism, body size, and faunal movements, emphasizing a poleward migration of fauna in response to rising temperatures. Panel B examines oxygen concentration, illustrating the impact of diminished oxygen levels on macrofaunal and megafaunal abundance, benthic biomass, and the cycling of nitrogen and carbon. Panel C depicts the impact of declining pH (ocean acidification) on metabolic energy demands, shell dissolution, and the abundance and diversity of calcifiers. Panel D demonstrates the impact of particulate organic carbon (POC) flux on microbial roles in carbon cycling, sediment mixing depth, biodiversity, and faunal abundance. Collectively, these panels highlight the interrelated and sequential effects of climate change stressors on the composition and operation of deep-sea ecosystems.

Increasing Ocean Temperatures and Thermal Resilience

Even small increases in ocean temperatures cause large changes for organisms, even in the deep-sea freezing temperatures. Often deep-sea animals are stenothermal – adapted to a small range of temperatures. Higher temperatures can disrupt cellular, and enzymatic functions leading to reduced metabolic performance and death in these species (Klein et al., 2018). Some of the species of deep-sea corals (such as Lophelia pertusa) are extremely sensitive to small changes in temperature. Coral bleaching, typically associated with shallow-water corals, has recently been observed in deep-sea communities due to increased water temperatures (Yum et al., 2017).

Species diversity also depends on how much temperature varies. Some species that live deep in the sea might shift to ever deeper waters in search of those more temperate climes. This is not always possible, though, due to limited suitable habitat and resources at greater depths. Such migratory events have the potential to alter deep-sea community composition and disrupt existing predator-prey interactions, leading to cascading effects throughout the ecosystem (Klein et al., 2018).

Ocean Acidification and Its Impact on Calcium-Dependent Structure

Ocean acidification derived from the uptake of excess atmospheric CO_2 represents a serious threat to organisms relying on calcium carbonate structures. When pH is lowered, the concentration of carbonate (CO3) ions is decreased and these ions are essential for shell and skeleton formation. These also serve as protective and supporting structures for many deep-sea organisms such as foraminifera, corals and mollusks (Danovaro et al., 2016).

This is especially true for deep-sea corals. These corals support important habitats for many marine species and act as biodiversity hotspots in the deep sea. As the ocean marbleheads, they get slower and weaker and more susceptible to cracking. It affects corals and the thousands of species that use corals as habitat or food (Yum et al., 2017).

Deoxygenation and Metabolic Strain

Deep-sea ecosystems are heavily impacted by climate change, and one of the primary effects is deoxygenation, or the reduction of dissolved oxygen levels in seawater. Oxygen minimum zones (OMZs) are naturally formed regions where there is very little oxygen availability; they are expanding due to increased stratification and reduced mixing between ocean layers. Many deep-sea creatures, including squids and some fish, have adapted to living with low levels of oxygen, but more drops could go beyond their physiological limits.

Shallow OMZs may limit vertical movement of species, and many deep-sea animals rely on surface water for food, meaning inability to migrate upward could disrupt feeding behaviors. Oxygen depletion, through species avoidance, can change the movement of these organisms, which can then lead to changes to deep-sea food webs and nutrient cycling (Danovaro et al., 2016).

Interruptions in Food Supply and Carbon Cycling

Climate change also influences the supply of organic material, or "marine snow," which falls from surface water to the depths of the ocean. The epipelagic zone is characterized by instability of the physical environment because of climate change affecting temperature, nutrient availability and shifting currents that influence primary productivity. Reduced surface productivity lowers the amount of food for deep sea organisms causing nutritional stress and possibly population size limitation (Danovaro et al., 2016).

Carbon cycle mediations drive deep sea functioning as a carbon sink the deep ocean is a sink for a lot of carbon and helps regulate climate on Earth. Therefore, any potential upset in biological pump, which transports carbon from near surface to deep ocean waters could reduce this storage capacity and thus cause more Global Warming (Yum et al., 2017) (Danovaro et al., 2016).

Migration Patterns and Captive Behavior of Fish

For many aquatic species, especially those living in the deep sea, migration is a survival strategy and a key to their reproductive biology. Long-term effects of climate change and human actions have slowly but continuously contaminated deep-sea fish migration and behaviour captured in captivity (Doi et al., 2021). Such dynamics are fundamental to our understanding of the conservation of deep-sea biodiversity and the future adaptive potential of species to changing environments (Doi et al., 2021).

Catalysts of Migration: Environmental Stressors and Habitat Degradation

Deep-sea fish often migrate based on environmental conditions (including food availability, oxygen concentrations, and temperature gradients). On the one hand, the ecosystem is now under new stresses due to climate change, which has changed where the birds are migrating (Doi et al., 2021). The decline in dissolved oxygen levels and rising ocean temperature drives species to cooler, more oxygen-rich regions, leading to the expansion of oxygen minimum zones (OMZs). These migrations are often vertical, with fish moving to deeper water to escape adverse conditions in the surface waters. However, this comes with a price, that areas below may not be sufficiently supplied and can sustain only small populations (Doi et al., 2021, Vereshchaka et al., 2019).

Bad human activities like deep-sea mining and bottom trawling also destroy habitats and lead to migration. Such activities disrupt sediment layers and destroy deep-sea environments that are critical feeding and spawning habitats for many deep-sea species. These habitats, once degraded, cause the fish to find new shelter relocating from one place to another leading to flooding of resource scarce fishes (Doi et al., 2021, Vereshchaka et al., 2019).

Case Studies on the Migration of Deep-Sea Species

Several studies have documented changes in the migrations of certain deep-sea animals. For example, black scabbardfish (Aphanopus carbo) have previously shown shifts in their geographical range due to increasing water temperatures (Doi et al., 2021). Similar to the discovery of commercially important species such as grenadiers and roughy oranges beyond their traditional distribution areas. This implies that environmental driving forces have an increasing influence on horizontal migrations in the deep sea (Danovaro et al., 2020).

One major example includes the vertical migrations of mesopelagic fish — a keystone component in the ocean carbon cycle. This transfer of carbon to the deep ocean is known as the biological pump, and these fish migrate daily between the surface and nutrient-rich, abyssal waters (Goulet et al., 2020). However, climate change will affect temperature gradients and shift oxygen content, altering their migration which may also impact the role that such carbon sequestration (Danovaro et al., 2020).

Obstacles in Investigating Deep-Sea Migration

Due to the technological and logistical challenges associated with observing deep-sea fish, understanding migration patterns is quite challenging. While data collection using, for example, acoustic telemetry and satellite tagging has improved , for many species investigations are still incomplete (Danovaro et al., 2020). The vast, remote nature of deep water limits long-term data collection on population dynamics and compositional change (Boyd et al., 2019).

Conduct and Physiological Reactions of Deep-Sea Fish in Captivity

Understanding how deep-sea fish behave when held in captivity is important for their physiology and ecological needs. However, reproducing deep-sea conditions in the lab or even in tanks is not easy, however. These organisms usually live at extreme depths, where pressures are titanic, temperatures are frigid, and light is nonexistent, and recreating these conditions is no mean feat. As a result, many deep-sea species exhibit behavioral changes or are unable to survive (Boyd et al., 2019).

Previous studies on anglerfish have shown that their habitat dictates their feeding and reproductive behavior. A lot of the time, they are faced with high-pressure and open systems in captivity that cannot always simulate what their natural habitat would be like causing metabolic demands to be high almost nonstop thus weakening and therefore shortening their life (Danovaro et al., 2020). Similarly, studies on deep-sea squid and isopods also highlighted the sensitivity of these species to both light exposure and temperature changes, providing an important context on the relevance of their natural habitat in maintaining physiological balance (Boyd et al., 2019).

Consequences for Conservation

Examination of migration patterns and captive behavior has significant consequences for conservation measures. Safeguarding migration routes and vital habitats is crucial for the survival of deep-sea organisms (Danovaro et al., 2020). Moreover, innovations in aquaculture methods for deep-sea species can support conservation initiatives by diminishing the dependence on wild populations for study or commercial use (Boyd et al., 2019).

Future Perspectives and Conservation Strategies

Covering over 60% of the Earth, the deep sea is home to much of the biodiversity of the planet and is a critical component of regulating our climate. Emerging technology is a growing resource that has been proposed to both assist in the development of policies to conserve deep sea biodiversity and protect biodiversity from impacts of climate change and human-mediated activity (Picardi et al., 2020). Deep-sea conservation also continues into the future with the realization that these problems need to be tackled by combining science, policy and society to address these issues and provide sustainable management of the most vulnerable ecosystem on earth (Xue et al., 2020)..

The Function of Advanced Technologies in Monitoring Deep-Sea Biodiversity

New technological developments have greatly enhanced exploration and knowledge of deep-sea ecosystems. AUVs are robots that operate underwater without a human on board; ROVs are uncrewed, tethered underwater vehicles and these instruments enable us to monitor and film deep-sea habitat in a footprint efficient way. Using advanced imaging systems such as high-definition cameras and other acoustic, optical, and video sensors which play a significant role in mapping habitats on the seabed, monitoring biodiversity, and changes to physical and biological patterns (Ramos et al., 2018). ROVs are an invaluable treasured in the identification of new deep-sea species and mapping inaccessible fragile coral ecosystems (Pai and Pai, 2021).

New genomic technologies, and particularly environmental DNA (eDNA) analysis, have the potential to revolutionize deep-sea conservation. Researchers use water samples to figure out what kind of species exist in the body of water by analyzing tiny traces of DNA or RNA that are left behind by an organism without physically catching it. This is a non-invasive method which allows widespread biodiversity monitoring and facilitates monitoring the effects of environmental change on deep-sea organisms (Belleter et al., 2019).

Deep-sea research is also incorporating AI and ML to an increasing extent, particularly for data analysis and for recognizing patterns in the data. Artificial Intelligence (AI) can analyze massive amounts of data obtained through AUV and ROV to recognize species, delineate areas, and forecast biological trends. These types of instruments are essential to investigate the lasting effects of climate change and other forms of human impact on deep-water environments (Martin and Gharib, 2018).

Strategies for Mitigating the Preservation of Deep-Sea Ecosystems

Local and global initiatives to tackle climate change are needed to build tethers between the deep sea and global society so that we can address its effects efficiently. Notably, the essential step to avoid ocean warming, acidification, and deoxygenation is mitigation of greenhouse gas emissions. Global treaties like the Paris Agreement play a fundamental role in encouraging states to pursue green policies that reduce carbon emissions (Binczyk et al., 2021).

Besides fighting climate change, fine-tuned mitigation strategies are needed to protect deep-sea ecosystems against irreversible direct human impacts. Objectives also include the regulation of operations such as deep-sea mining, bottom trawling and oil drilling to prevent habitat destruction. Buffer zones and exclusion areas may reduce the impacts of these operations on sensitive ecosystems (Vanreusel et al., 2016).

Policies and Global Cooperation

International collaboration is needed to conserve many deep-sea systems as these areas lie well beyond a number of jurisdictions, often in the region of international waters. Mining and other activities in these areas are regulated by the International Seabed Authority (ISA). More policy efforts and enforcement are needed to shield deep-sea environments from industrial activity (Xue et al., 2020)

Marine protected areas are among the best tools avaiable for conserving marine biodiversity and the establishment of such zones in the deep sea has become a topic of ever-increasing interest. Such regions limit human activity, permitting the ecosystem to override. Examples include Coral Sea Marine Park and Ross Sea Region Marine Protected Area7 and deliver substantial protection to key species (Benoist et al., 2019).

The Potential of Public Awareness and Citizen Science

Enhancing public knowledge of the significance of deep-sea ecosystems is a crucial element of conservation efforts. Documentaries, public outreach projects, and educational activities can underscore the importance of deep-sea biodiversity, and the challenges encountered. Citizen science initiatives, in which individuals participate in data gathering and analysis, can also serve a significant purpose. Crowdsourcing platforms enable volunteers to assist in identifying species in deep-sea footage or in analyzing satellite data pertaining to ocean health (Zhang et al., 2016).

CONCLUSION

Occupying the majority of the earth, the deep sea is critical to the health of our planet but also very elusive with unique physiological and morphological adaptations of its inhabitants necessary to live under extreme pressure, in seemingly perpetual darkness, and with limited access to nutrients. However, the adaptations that enable life in the deep sea, may leave deep-sea animals vulnerable to environmentally driven climatic and anthropogenic change. This review highlights major findings on the impact of ocean warming, acidification, deoxygenation and habitat degradation on deep-sea ecosystems, emphasizing their key role in biodiversity and climate regulation at a global scale. With the development of more powerful technologies such as remotely operated vehicles (ROVs), genomic tools, and artificial intelligence (AI), we can now study these ecosystems with greater efficiency and offer important information about migration patterns, ecological roles, and potential impacts of environmental stressors. Despite these advances, major deficits remain, including a lack of understanding of prolonged physiological responses to chronic stressors, limited information on migratory pathways, and molecular processes controlling those deep-sea adaptations. Solution of these gaps needs transdisciplinary and experimental studies that simulate climate change, use modern genomics tools, and quantify the contribution of deep-sea systems to global carbon cycling. In addition, conservation should also focus on combating negative human impacts such as deep-sea mining and improving protection of places that are important to marine life. This review emphasizes the need for international collaboration, implementation of proper policy, and public engagement in the efficient management of deep-sea habitats. Although challenges abound, I believe the future of deep-sea science offers great potential to improve our science and policy advice and thereby maintain the health and resilience of irreplaceable deep-sea ecosystems.

REFERENCES

Barrouin-Melo, S. M., Anturaniemi, J., Sankari, S., Griinari, M., Atroshi, F., Ounjaijean, S., & Hielm-Björkman, A. K. (2016). Evaluating oxidative stress, serological- and haematological status of dogs suffering from osteoarthritis, after supplementing their diet with fish or corn oil. *Lipids in Health and Disease*, *15*(1). https://doi.org/10.1186/s12944-016-0304-6

Belleter, D. J., Braga, J., & Pettersen, K. Y. (2019). Experimental verification of a coordinated path-following strategy for Underactuated marine vehicles. *Frontiers in Robotics and AI*, *6*. https://doi.org/10.3389/frobt.2019.00035

Benoist, N. M., Morris, K. J., Bett, B. J., Durden, J. M., Huvenne, V. A., Le Bas, T. P., Wynn, R. B., Ware, S. J., & Ruhl, H. A. (2019). Monitoring mosaic biotopes in a marine conservation zone by autonomous underwater vehicle. *Conservation Biology*, *33*(5), 1174-1186. https://doi.org/10.1111/cobi.13312

Binczyk, F., Prazuch, W., Bozek, P., & Polanska, J. (2021). Radiomics and artificial intelligence in lung cancer screening. *Translational Lung Cancer Research*, *10*(2), 1186-1199. https://doi.org/10.21037/tlcr-20-708

Boyd, P. W., Claustre, H., Levy, M., Siegel, D. A., & Weber, T. (2019). Multi-faceted particle pumps drive carbon sequestration in the ocean. *Nature*, *568*(7752), 327-335. https://doi.org/10.1038/s41586-019-1098-2

Castillo, A., Alvarez, A., Cuzon, G., Suárez, J., & Gaxiola, G. (2017). Glycemic response after glucose oral administration of wild juvenile red grouper Epinephelus morio fed two different diets. *Fish Physiology and Biochemistry*, *44*(1), 219-226. https://doi.org/10.1007/s10695-017-0426-4

Cheng, J., Hui, M., & Sha, Z. (2019). Transcriptomic analysis reveals insights into deep-sea adaptations of the dominant species, Shinkaia crosnieri (Crustacea: Decapoda: Anomura), inhabiting both hydrothermal vents and cold seeps. *BMC Genomics*, *20*(1). https://doi.org/10.1186/s12864-019-5753-7

Collins, F. W., Walsh, C. J., Gomez-Sala, B., Guijarro-García, E., Stokes, D., Jakobsdóttir, K. B., Kristjánsson, K., Burns, F., Cotter, P. D., Rea, M. C., Hill, C., & Ross, R. P. (2021). The microbiome of deep-sea fish reveals new microbial species and a sparsity of antibiotic resistance genes. *Gut Microbes*, *13*(1). https://doi.org/10.1080/19490976.2021.1921924

Crowe-Riddell, J. M., Snelling, E. P., Watson, A. P., Suh, A. K., Partridge, J. C., & Sanders, K. L. (2016). The evolution of scale sensilla in the transition from land to sea in elapid snakes. *Open Biology*, *6*(6), 160054. https://doi.org/10.1098/rsob.160054

Danovaro, R., Fanelli, E., Aguzzi, J., Billett, D., Carugati, L., Corinaldesi, C., Dell'Anno, A., Gjerde, K., Jamieson, A. J., Kark, S., McClain, C., Levin, L., Levin, N., Ramirez-Llodra, E., Ruhl, H., Smith, C. R., Snelgrove, P. V., Thomsen, L., Van Dover, C. L., … Yasuhara, M. (2020). Ecological variables for developing a global deep-ocean monitoring and conservation strategy. *Nature Ecology & Evolution*, *4*(2), 181-192. https://doi.org/10.1038/s41559-019-1091-z

Danovaro, R., Molari, M., Corinaldesi, C., & Dell'Anno, A. (2016). Macroecological drivers of archaea and bacteria in benthic deep-sea ecosystems. *Science Advances*, *2*(4). https://doi.org/10.1126/sciadv.1500961

De Busserolles, F., & Marshall, N. J. (2017). Seeing in the deep-sea: Visual adaptations in lanternfishes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1717), 20160070. https://doi.org/10.1098/rstb.2016.0070

Doi, H., Yasuhara, M., & Ushio, M. (2021). Causal analysis of the temperature impact on deep-sea biodiversity. *Biology Letters*, *17*(7), 20200666. https://doi.org/10.1098/rsbl.2020.0666

Freed, L. L., Easson, C., Baker, L. J., Fenolio, D., Sutton, T. T., Khan, Y., Blackwelder, P., Hendry, T. A., & Lopez, J. V. (2019). Characterization of the microbiome and bioluminescent symbionts across life stages of Ceratioid Anglerfishes of the Gulf of Mexico. *FEMS Microbiology Ecology*, *95*(10). https://doi.org/10.1093/femsec/fiz146

Frühauf, A., Niedermeier, M., & Kopp, M. (2020). Intention to engage in winter sport in climate change affected environments. *Frontiers in Public Health*, *8*. https://doi.org/10.3389/fpubh.2020.598297

Gan, Z., Yuan, J., Liu, X., Dong, D., Li, F., & Li, X. (2020). Comparative transcriptomic analysis of deep- and shallow-water barnacle species (Cirripedia, Poecilasmatidae) provides insights into deep-sea adaptation of sessile crustaceans. *BMC Genomics*, *21*(1). https://doi.org/10.1186/s12864-020-6642-9

Goulet, P., Guinet, C., Campagna, C., Campagna, J., Tyack, P. L., & Johnson, M. (2020). Flash and grab: Deep-diving southern elephant seals trigger anti-predator flashes in bioluminescent prey. *Journal of Experimental Biology*, *223*(10). https://doi.org/10.1242/jeb.222810

Ham, J. Y., & Shon, Y. H. (2020). Natural magnesium-enriched deep-sea water improves insulin resistance and the lipid profile of Prediabetic adults: A randomized, double-blinded crossover trial. *Nutrients*, *12*(2), 515. https://doi.org/10.3390/nu12020515

Hittle, K. A., Kwon, E. S., & Coughlin, D. J. (2021). Climate change and anadromous fish: How does thermal acclimation affect the mechanics of the myotomal muscle of the Atlantic salmon, *Salmo salar*? *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, *335*(3), 311-318. https://doi.org/10.1002/jez.2443

Isogai, Y., Imamura, H., Nakae, S., Sumi, T., Takahashi, K., Nakagawa, T., Tsuneshige, A., & Shirai, T. (2018). Tracing whale myoglobin evolution by resurrecting ancient proteins. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-34984-6

Kang, P., Wang, Y., Li, X., Wan, Z., Wang, X., Zhu, H., Wang, C., Zhao, S., Chen, H., & Liu, Y. (2019). Effect of flaxseed oil on muscle protein loss and carbohydrate oxidation impairment in a pig model after lipopolysaccharide challenge. *British Journal of Nutrition*, *123*(8), 859-869. https://doi.org/10.1017/s0007114519002393

Klein, E. S., Hill, S. L., Hinke, J. T., Phillips, T., & Watters, G. M. (2018). Impacts of rising sea temperature on krill increase risks for predators in the Scotia sea. *PLOS ONE*, *13*(1), e0191011. https://doi.org/10.1371/journal.pone.0191011

Martin, N., & Gharib, M. (2018). On the role of tip curvature on flapping plates. *Bioinspiration & Biomimetics*, *13*(2), 026001. https://doi.org/10.1088/1748-3190/aaa1c0

Masanari, M., Fujii, S., Kawahara, K., Oki, H., Tsujino, H., Maruno, T., Kobayashi, Y., Ohkubo, T., Wakai, S., & Sambongi, Y. (2016). Comparative study on stabilization mechanism of monomeric cytochrome c 5 from deep-sea piezophilic Shewanella violacea. *Bioscience, Biotechnology, and Biochemistry*, *80*(12), 2365-

2370. https://doi.org/10.1080/09168451.2016.1232155

Mu, W., Liu, J., & Zhang, H. (2018). Complete mitochondrial genome of Benthodytes marianensis (Holothuroidea: Elasipodida: Psychropotidae): Insight into deep sea adaptation in the sea cucumber. *PLOS ONE*, *13*(11), e0208051. https://doi.org/10.1371/journal.pone.0208051

Nakaya, K., Tomita, T., Suda, K., Sato, K., Ogimoto, K., Chappell, A., Sato, T., Takano, K., & Yuki, Y. (2016). Slingshot feeding of the goblin shark Mitsukurina owstoni (Pisces: Lamniformes: Mitsukurinidae). *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep27786

Pai, V. V., & Pai, R. B. (2021). Artificial intelligence in dermatology and healthcare: An overview. *Indian Journal of Dermatology, Venereology and Leprology*, *0*, 1-11. https://doi.org/10.25259/ijdvl_518_19

Petitjean, Q., Jacquin, L., LeHénaff, M., Perrault, A., Cousseau, M., Laffaille, P., & Jean, S. (2020). Dose- and time-dependent effects of an immune challenge on fish across biological levels. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, *335*(2), 250-264. https://doi.org/10.1002/jez.2430

Picardi, G., Chellapurath, M., Iacoponi, S., Stefanni, S., Laschi, C., & Calisti, M. (2020). Bioinspired underwater legged robot for seabed exploration with low environmental disturbance. *Science Robotics*, *5*(42). https://doi.org/10.1126/scirobotics.aaz1012

Ramos, A. G., García-Garrido, V. J., Mancho, A. M., Wiggins, S., Coca, J., Glenn, S., Schofield, O., Kohut, J., Aragon, D., Kerfoot, J., Haskins, T., Miles, T., Haldeman, C., Strandskov, N., Allsup, B., Jones, C., & Shapiro, J. (2018). Lagrangian coherent structure assisted path planning for transoceanic autonomous underwater vehicle missions. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-23028-8

Röthig, T., Yum, L. K., Kremb, S. G., Roik, A., & Voolstra, C. R. (2017). Microbial community composition of deep-sea corals from the Red Sea provides insight into functional adaption to a unique environment. *Scientific Reports*, *7*(1). https://doi.org/10.1038/srep44714

Tabari, M. A., Youssefi, M. R., Hosseinifard, S. M., Moghaddamnia, A. A., Kazemi, S., Sadati, N. Y., Jalali Mothahari, A., & Giorgi, M. (2020). Pharmacokinetics of levamisole after intramuscular and oral administrations to caspian salmon (*Salmo trutta caspius*). *Journal of Veterinary Pharmacology and Therapeutics*, *43*(3), 276-281. https://doi.org/10.1111/jvp.12856

Tortorella, E., Tedesco, P., Palma Esposito, F., January, G. G., Fani, R., Jaspars, M., & De Pascale, D. (2018). Antibiotics from deep-sea microorganisms: Current discoveries and perspectives. *Marine Drugs*, *16*(10), 355. https://doi.org/10.3390/md16100355

Tsutsui, K., Shimada, E., Ogawa, T., & Tsuruwaka, Y. (2016). A novel fluorescent protein from the deep-sea anemone Cribrinopsis japonica (Anthozoa: Actiniaria). *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep23493

Vanreusel, A., Hilario, A., Ribeiro, P. A., Menot, L., & Arbizu, P. M. (2016). Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep26808

Vereshchaka, A. L., Lunina, A. A., & Sutton, T. (2019). Assessing deep-pelagic shrimp biomass to 3000 m in the Atlantic Ocean and ramifications of Upscaled global biomass. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-42472-8

Weber, A. A., Hugall, A. F., & O'Hara, T. D. (2020). Convergent evolution and structural adaptation to the deep ocean in the protein-folding Chaperonin CCTα. *Genome Biology and Evolution*, *12*(11), 1929-1942. https://doi.org/10.1093/gbe/evaa167

Xie, Z., Jian, H., Jin, Z., & Xiao, X. (2018). Enhancing the adaptability of the deep-sea bacterium Shewanella piezotolerans WP3 to high pressure and low temperature by experimental evolution under H2O2 stress. *Applied and Environmental Microbiology*, *84*(5). https://doi.org/10.1128/aem.02342-17

Xue, Y., Ding, M. Q., & Lu, X. (2020). Learning to ENCODE cellular responses to systematic perturbations with deep generative models. *npj Systems Biology and Applications*, *6*(1). https://doi.org/10.1038/s41540-020-00158-2

Yum, L. K., Baumgarten, S., Röthig, T., Roder, C., Roik, A., Michell, C., & Voolstra, C. R. (2017). Transcriptomes and expression profiling of deep-sea corals from the Red Sea provide insight into the biology of azooxanthellate corals. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-

017-05572-x

Zeng, X., Zhang, Y., Meng, L., Fan, G., Bai, J., Chen, J., Song, Y., Seim, I., Wang, C., Shao, Z., Liu, N., Lu, H., Fu, X., Wang, L., Liu, X., Liu, S., & Shao, Z. (2020). Genome sequencing of deep-sea hydrothermal vent snails reveals adaptions to extreme environments. *GigaScience*, *9*(12). https://doi.org/10.1093/gigascience/giaa139

Zhang, T., Shi, H., Chen, L., Li, Y., & Tong, J. (2016). AUV positioning method based on tightly coupled SINS/LBL for underwater acoustic Multipath propagation. *Sensors*, *16*(3), 357. https://doi.org/10.3390/s16030357