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A Systematic Review on Challenges and Conservation Strategies for Marine Megafauna

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Authors' contributions

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ABSTRACT

Marine megafauna play pivotal roles in oceanic ecosystems, contributing to their health, functionality, and biodiversity. These species are facing escalating threats, from direct harms such as overhunting to indirect pressures like habitat degradation and climate change. This systematic review explores the challenges confronting marine megafauna, examines current conservation strategies, and explores innovative future strategies. Current efforts, while beneficial, often fail to

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address socio-economic factors and cumulative threat impacts, and lack robust long-term outcome evaluations. Potential strategies, leveraging emerging technologies, climate-smart conservation, sustainable blue economies, and rights-based approaches, are discussed. Despite their potential, these strategies present challenges, necessitating further interdisciplinary, social, cumulative impact, and long-term monitoring research. Understanding and addressing these aspects is essential for the development of holistic, effective, and sustainable marine megafauna conservation strategies. Future research should address gaps in species-specific knowledge, socio-economic understanding, cumulative threat assessments, and long-term conservation outcomes to provide a more comprehensive approach towards the protection of these vital species.

Keywords: Megafauna; conservation; threats; innovation; research.

1. INTRODUCTION

Marine megafauna, a diverse group of large-bodied organisms that inhabit the oceans, including cetaceans (whales, dolphins, and porpoises), pinnipeds (seals, sea lions, and walruses), sirenians (dugongs and manatees), marine reptiles (turtles and marine iguanas), and large fish species (sharks, rays, and tunas), have a profound influence on the structure and function of marine ecosystems [1]. These species serve as keystone species, modulating biodiversity and ecosystem productivity, aiding in nutrient cycling, and impacting commercial fisheries [2]. Their large body sizes, relatively long lifespans, and wide-ranging behaviors make them highly influential within their ecosystems, but also particularly susceptible to human-induced changes [3]. As apex predators and ecosystem engineers, they also have a strong influence on the trophic dynamics and physical structure of their environments [4]. For example, cetaceans, through their feeding and defecation behaviors, help transport nutrients across different oceanic zones, thereby contributing significantly to primary productivity and the biological carbon pump [5]. Despite their importance, many species of marine megafauna are under threat due to a multitude of anthropogenic factors including overfishing, bycatch, pollution, habitat degradation, and climate change [6].The International Union for Conservation of Nature (IUCN) has listed a significant proportion of these species as vulnerable, endangered, or critically endangered, underlining the urgency of addressing these threats (Table 1) [7]. The focus on challenges and conservation strategies for marine megafauna is crucial for several reasons. First, as top predators, these species play a key role in maintaining the balance of marine ecosystems. Their loss can lead to cascading effects on lower trophic levels, potentially resulting in ecosystem instability [8]. Second, the conservation of these species often necessitates broad-scale, ecosystem-level management, which can have far-reaching benefits for biodiversity and ecosystem health [9]. Lastly, these charismatic species serve as important flagships for marine conservation, drawing attention to issues that may otherwise be overlooked [10].

Given the complexity and scale of the challenges facing marine megafauna, a systematic review of the current knowledge on these issues is warranted. This review will allow us to evaluate the effectiveness of current conservation strategies and identify knowledge gaps that need to be addressed. As recent advancements in technologies such as satellite tagging and genetic analysis have provided unprecedented insights into the life histories, behaviors, and threats facing these species [11], a comprehensive synthesis of this new knowledge will be invaluable in informing future research and conservation actions. Systematic reviews, by nature, provide a transparent and replicable means of synthesizing a large body of research, thereby minimizing bias and providing a reliable foundation for decision-making [12]. In the context of marine megafauna conservation, such a review will allow us to consolidate information on the diverse array of threats faced by these species, evaluate the efficacy of existing conservation strategies, and highlight priority areas for future action. It will contribute to the development of evidence-based conservation strategies, ensuring that resources are allocated in a manner that maximizes their impact on the conservation of these ecologically important species.

2. HISTORY AND EVOLUTION OF MARINE MEGAFAUNA

The study of the history and evolution of marine megafauna necessitates diving deep into the annals of Earth's past, as these species are an integral part of our planet's natural history (Table 2). The evolution of marine megafauna is an

exemplary tale of adaptation and survival, encapsulating numerous instances of terrestrial species re-entering marine habitats, a process known as secondary aquatic adaptation [13]. One of the earliest instances of secondary aquatic adaptation is found in the lineage leading to today's cetaceans, approximately 50 million years ago [14] Archaeocetes, the ancient ancestors of whales, are believed to have evolved from terrestrial, hoofed mammals known as artiodactyls, a group that includes deer, cows, and pigs. Through a series of morphological changes such as the development of a streamlined body, paddle-like limbs, and a dorsal blowhole, these terrestrial animals transitioned to a fully aquatic lifestyle [15]. Pinnipeds (seals, sea lions, and walruses) evolved from terrestrial ancestors around 23 million years ago [16]. Their transition to an aquatic environment is marked by the evolution of flippers and a fusiform body shape for efficient swimming. Marine reptiles, such as sea turtles, also have terrestrial ancestors. It's estimated that their adaptation to marine life occurred approximately 110 million years ago in the Cretaceous period, and involved significant changes like the development of a flattened, paddle-like limb and a streamlined shell [17]. Large fish species, including sharks, have an even older evolutionary history, dating back approximately 420 million years [18]. These species have evolved a range of unique adaptations to their marine environment, such as electroreception and the ability to osmoregulate in varying salinities.

3. MARINE MEGAFAUNA

Marine megafauna are typically defined as marine species that reach a large size at adulthood, usually exceeding 100 kg in weight [19]. This group is characterized by its broad taxonomic diversity, encompassing various classes of vertebrates including mammals, reptiles, and fish (Table 3). Examples of marine mammalian megafauna include cetaceans like the blue whale (*Balaenoptera musculus*), the largest animal ever known to have lived on Earth, and the sperm whale (*Physeter macrocephalus*), known for its deep diving abilities and large brain size [20] The group also includes pinnipeds, such as the elephant seal (*Mirounga leonina*), renowned for its size and long-distance migrations [21]. Marine reptiles such as the leatherback sea turtle (*Dermochelys coriacea*) and saltwater crocodile (*Crocodylus porosus*) are also part of marine megafauna. Among the fish, the whale shark (*Rhincodon typus*), the largest known extant fish species, and the manta ray (*Manta birostris*), the largest ray, are notable members of marine megafauna [22].

4. MARINE MEGAFAUNA TO THE HEALTH AND FUNCTIONING OF OCEAN ECOSYSTEMS

Marine megafauna play a pivotal role in maintaining the health and functioning of ocean ecosystems. They serve as apex predators, exerting top-down control on food webs, helping to maintain biodiversity and stability in their ecosystems [23]. Their predation pressure can regulate the abundance and behavior of their prey, with effects cascading down to lower trophic levels, a phenomenon known as trophic cascades [24]. Marine megafauna contribute to nutrient cycling. Whales, for instance, play a vital role in the 'biological pump', facilitating the transfer of nutrients from nutrient-rich deep waters to the nutrient-poor surface waters [25]. This 'whale pump' enhances primary productivity, which in turn, supports higher trophic levels. The large-scale movements of marine megafauna connect disparate marine ecosystems, both horizontally across latitudes and longitudes, and vertically across depths. These movements aid in the transportation and distribution of energy and nutrients, influencing productivity and diversity in various ecosystems [26]. Consequently, the loss or reduction of marine megafauna can have far-reaching consequences, leading to ecosystem

Table 1. Threats, current and innovative conservation strategies for selected marine megafauna species

Species	Main threats	Current conservation strategies	Potential innovative strategies
Blue Whale	Ship strikes, noise pollution, climate change	Marine Protected Areas (MPAs), shipping regulation	Use of AI and remote sensing for monitoring and management
Sea Turtles	Bycatch, habitat degradation, climate change	Nesting beach protection, bycatch reduction devices	eDNA for population monitoring, climate-smart conservation
Dugong	Hunting, habitat loss, pollution	Hunting restrictions, seagrass habitat conservation	Rights-based approaches, sustainable blue economy initiatives

Table 2. Key events in the history and evolution of selected marine megafauna

Period (millions of years ago)	Evolutionary events	Species
220-200	First appearance of ichthyosaurs, marine reptiles resembling dolphins	Ichthyosaurs
110-90	First appearance of plesiosaurs, long-necked marine reptiles	Plesiosaurs
66-30	Evolution and diversification of early cetaceans (whales, dolphins, and porpoises) from land-dwelling ancestors	Early Cetaceans
35-30	Evolution of the first sirenians, including ancestors of dugongs and manatees	Early Sirenians
15-10	Diversification of baleen whales following the development of baleen plates for filter feeding	Baleen Whales
6-4	Evolution of modern sea turtle lineages	Modern Sea Turtles
5-2	Diversification of pinnipeds (seals, sea lions, and walruses)	Pinnipeds
2-0	Evolution and diversification of modern cetacean species	Modern Cetaceans

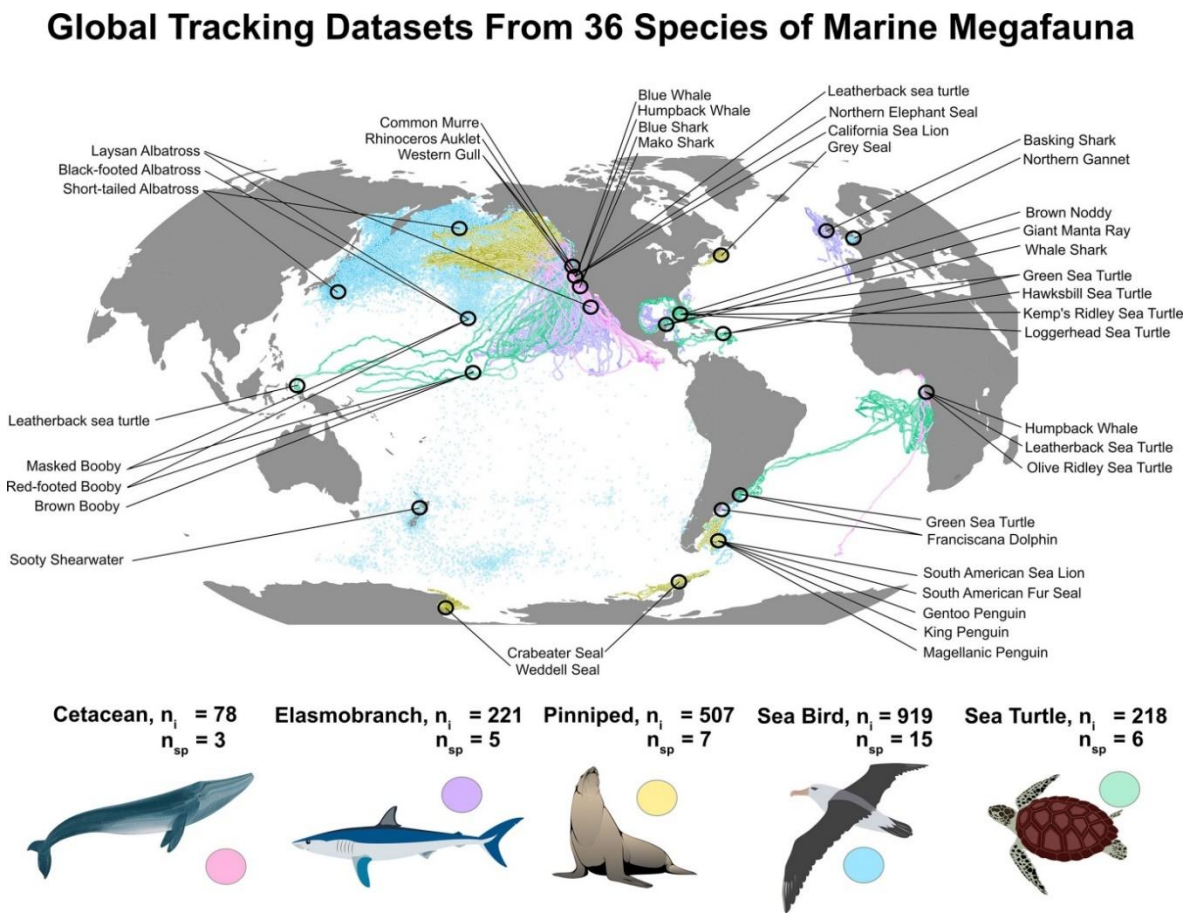

Image 1. Mismatches in scale between highly mobile marine megafauna and marine protected areas

(Source: https://www.frontiersin.org/)

instability and loss of resilience [27]. Understanding and mitigating the threats to marine megafauna, and developing effective conservation strategies is not only crucial for the survival of these species, but also for the overall health and functioning of our planet's marine ecosystems.

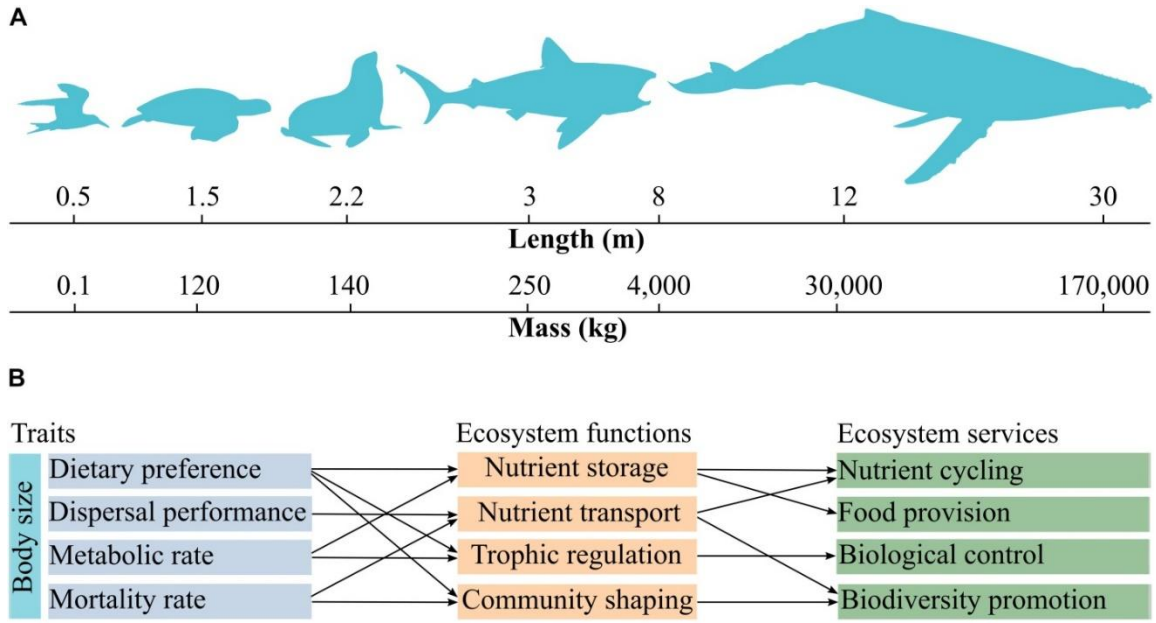

Image 2. Traits shared by marine megafauna and their relationships with ecosystem functions and services

(Source: https://www.frontiersin.org/)

Table 3. Overview of selected marine megafauna species

Species	Defining Features	Typical Habitat	Role in Ecosystem
Blue Whale	The largest animal ever to have lived on Earth, reaching up to 100 feet in length.	Found in all the world's oceans, except the Arctic, primarily in cold, productive waters.	As predators, they play a key role in maintaining the health of the ecosystem. Their fecal plumes also promote primary productivity by increasing nutrient availability.
Great White Shark	Notable for their size, with larger females individuals growing up to 20 feet in length.	They are found in cool, coastal waters all over the world.	They are apex predators, maintaining the species below them in the food chain and serving as an indicator for ocean health.
Leatherback Turtle	The largest of all living turtles and the fourth-heaviest modern reptile.	They are found in the open ocean, as far north as Alaska and as far south as the southern tip of Africa.	They influence jellyfish populations, helping to keep these potentially explosive populations in check.
Dugong	A medium-sized marine mammal, it is one of four living species of the order Sirenia, which also includes three species of manatees.	Found in warm coastal waters from the western Pacific Ocean to the eastern coast of Africa.	They influence seagrass ecosystems and associated species as prolific grazers.

5. METHODOLOGY

The process for selecting studies and articles for this systematic review adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [28]. Initial searches were performed using online databases such as Web of Science, PubMed, ScienceDirect, JSTOR, and Google Scholar. The search strategy was developed using a combination of keywords and controlled vocabulary relevant to the review topic. The

keywords included terms such as "marine megafauna", "conservation", "challenges", "threats", "strategies", and "ecosystem". Boolean operators ("AND", "OR") were used to link the terms, refining the search. Studies and articles published in English from 2000 until 2023 were considered. The search focused on original research articles, literature reviews, reports, and policy documents. Conference proceedings, theses, dissertations, and book chapters were also considered if they met the inclusion criteria. The titles and abstracts of the returned results were screened for relevance. If they seemed to address the topic of challenges and conservation strategies for marine megafauna, the full text was retrieved and assessed for eligibility. This screening process was carried out independently by two reviewers, and disagreements were resolved through discussion or the involvement of a third reviewer.

5.1 Criteria Used to Evaluate the Quality and Relevance of the Sources

The quality and relevance of the sources were evaluated using predefined criteria. For a source to be considered relevant, it had to focus on marine megafauna, addressing either the challenges they face or the strategies employed for their conservation. The quality of the sources was assessed using a critical appraisal tool, adapted from the Joanna Briggs Institute's critical appraisal tools for use in JBI systematic reviews [29]. The tool evaluated the methodological quality of the studies based on parameters like clarity of objectives, appropriateness of design, adequacy of sample size, soundness of data collection and analysis methods, and credibility of results and conclusions. A source was considered of high quality if it met most of the criteria on the appraisal tool. Low-quality sources were excluded from the review.

5.2 Process for Extracting and Synthesizing Data from the Sources

Data extraction was performed using a standardized form designed to capture information pertinent to the review objectives. The extracted data included the author(s), year of publication, type of marine megafauna studied, location of study, key findings related to the challenges faced by the species, and conservation strategies proposed or implemented. Data synthesis was conducted through a narrative synthesis approach, given the likely heterogeneity in the types and designs of the included studies [30]. The findings were grouped and analyzed based on the type of marine megafauna, the challenges they face, and the conservation strategies discussed. Trends and patterns across the studies were identified, and the implications of these findings for the conservation of marine megafauna were discussed.

6. CHALLENGES FACED BY MARINE MEGAFAUNA

6.1 Specific Threats to Different Species of Marine Megafauna

Marine megafauna face a multitude of threats, both direct and indirect, stemming from human activities. These threats are multifaceted, varying across species and geographies, and are often interconnected, exacerbating their impacts.

6.1.1 Direct threats

1. **Hunting:** Historically, marine megafauna have been targeted for their meat, blubber, bones, and other body parts. For instance, whaling decimated numerous cetacean populations globally during the 19th and 20th centuries [31] Although commercial whaling has largely ceased due to international regulations, some countries still practice whaling for scientific research or cultural purposes [32]. Similarly, hunting of seals for fur, meat, and oil has impacted populations in the Arctic and sub-Arctic regions [33].
2. **Bycatch and Entanglement:** Bycatch, the unintentional capture of non-target species in fishing gear, is a significant threat to marine megafauna. Dolphins, turtles, sharks, and seals are often caught in gillnets, trawls, and longlines, leading to serious injury or death [34]. In addition, discarded or lost fishing gear, known as ghost gear, can entangle marine megafauna, causing drowning, impaired movement, or infection [35].

6.1.2 Indirect threats

1. **Habitat Degradation:** Coastal development, pollution, and destructive fishing practices can degrade marine habitats, affecting the food resources, breeding grounds, and migratory routes of marine megafauna. For instance, coral reef degradation due to blast fishing and ocean

acidification can reduce the habitat and prey availability for species like the manta ray [36].

2. **Climate Change Impacts:** Climate change, through increasing ocean temperatures, acidification, sea level rise, and shifts in ocean currents, can disrupt the life cycles and distribution of marine megafauna. Changes in sea ice extent due to global warming can affect ice-dependent species like polar bears and seals [37]. Warmer sea temperatures can also alter the distribution of prey species, forcing predators like sharks and whales to shift their ranges [38].

6.2 Exploration of Case Studies Illustrating These Threats

1. **Vaquita *(Phocoena sinus)* Bycatch:** The vaquita, the world's smallest and most endangered marine mammal, provides a stark example of the impact of bycatch. Found only in the Gulf of California, Mexico, their population has plummeted due to accidental entanglement in gillnets used for fishing totoaba, a critically endangered fish also found in the Gulf [39].
2. **Leatherback Sea Turtle *(Dermochelys coriacea)* and Climate Change:** Leatherback sea turtles, the largest of all living turtles, are experiencing threats from climate change. Rising temperatures can skew sex ratios in hatchlings as the sex of these turtles is temperature-dependent. Moreover, sea level rise and increased storm activity can erode and destroy their nesting beaches [40].

6.3 Severity and Urgency of These Challenges

The severity and urgency of these challenges cannot be overstated. The IUCN Red List of Threatened Species reports alarming statistics: 33% of shark species, 5 out of 7 species of marine turtles, and 26% of marine mammal species are threatened with extinction [41]. These numbers underscore the immediate need to address the threats facing marine megafauna. The urgency is further heightened by the fact that marine megafauna, as apex predators and ecosystem engineers, play vital roles in maintaining the structure and function of marine ecosystems. The loss or decline of these species could trigger cascading effects, leading to ecosystem instability and loss of biodiversity.

6.4 Conservation Strategies in Place

Various conservation strategies have been developed and implemented to protect marine megafauna. These strategies are often multi-faceted, combining legal, technical, and socio-economic approaches.

1. **Protected Areas:** The establishment of Marine Protected Areas (MPAs) and Marine Reserves is a critical tool for the protection of marine megafauna. These areas limit or prohibit activities like fishing and resource extraction, allowing species to recover [42].
2. **Legislation and Regulation:** International treaties, national laws, and regulations are also key. The Convention on International Trade in Endangered Species (CITES) controls the trade of marine megafauna species and their products, while the International Whaling Commission (IWC) regulates whaling activities [43]. National legislation, such as the U.S. Endangered Species Act and Marine Mammal Protection Act, offers additional protection.
3. **Bycatch Reduction:** Bycatch reduction strategies, such as modifications to fishing gear (e.g., turtle excluder devices, bird-scaring lines), spatial and temporal fishing restrictions, and bycatch quotas, have been developed to reduce the incidental capture of marine megafauna [44].
4. **Community Engagement and Education:** Engaging local communities and improving public awareness is fundamental. Community-based conservation programs, such as ecotourism and citizen science projects, can provide alternative livelihoods and encourage stewardship of marine resources [45].

6.5 Evaluation of the Effectiveness of These Strategies

The effectiveness of conservation strategies varies, influenced by factors like enforcement, funding, political will, and community support.

1. **Protected Areas:** While MPAs can be effective in increasing species abundance and diversity, their success often hinges on proper management and enforcement [46].
2. **Legislation and Regulation:** International treaties and national legislation have made significant strides in marine megafauna

conservation. For instance, the ban on commercial whaling by the IWC has allowed several whale populations to recover [47]. However, compliance and enforcement remain challenging.

3. **Bycatch Reduction:** Bycatch reduction strategies can effectively reduce megafauna mortality. For instance, the use of turtle excluder devices has significantly reduced sea turtle bycatch in shrimp trawl fisheries [48].The adoption of such strategies is not universal and often faces resistance from fishers.
4. **Community Engagement and Education:** These efforts are critical for long-term conservation success. Yet, they are often under-resourced and undervalued, and their impacts can be challenging to measure.

7. CASE STUDIES OF SUCCESSFUL CONSERVATION EFFORTS

1. **Humpback Whale Recovery:** The humpback whale is a compelling example of successful conservation. Once near extinction due to commercial whaling, their numbers have rebounded since the international moratorium on commercial whaling in 1982, demonstrating the power of regulatory action [49].
2. **Sea Turtle Conservation in Costa Rica:** The community-based conservation program in Tortuguero, Costa Rica, has played a crucial role in the recovery of green turtle populations. This program combines research, ecotourism, and community engagement, providing an economically viable alternative to turtle egg poaching [50].

8. EXPLORATION OF CHALLENGES IN IMPLEMENTING THESE STRATEGIES

Implementing these strategies is fraught with challenges, including enforcement difficulties, economic pressures, and socio-political conflicts. For example, MPAs often face issues of illegal fishing and resource extraction, highlighting the need for effective enforcement mechanisms [51]. Similarly, economic and cultural pressures can hinder the adoption of bycatch reduction technologies and the compliance with conservation regulations [52]. Climate change exacerbates these challenges by altering marine habitats and increasing the uncertainty surrounding conservation efforts. Strategies need to be adaptable and resilient to changing conditions [53].

9. INNOVATIONS AND FUTURE STRATEGIES FOR CONSERVATION

The future of marine megafauna conservation will hinge on developing and applying innovative strategies, rooted in advances in science and technology, policy, and social engagement.

1. **Emerging Technologies:** The rise of technologies such as artificial intelligence (AI), remote sensing, and environmental DNA (eDNA) offer exciting opportunities for marine conservation. For instance, AI can aid in identifying and tracking marine megafauna, enhancing monitoring and research capabilities [54]. eDNA, on the other hand, can provide non-invasive methods of detecting and monitoring species in the ocean, offering a powerful tool for conservation [55].
2. **Climate-Smart Conservation:** As climate change continues to impact marine ecosystems, conservation strategies need to be 'climate-smart'-considering how climate change affects marine megafauna and their habitats and implementing adaptive measures [56].
3. **Sustainable Blue Economy:** The 'Blue Economy' concept emphasizes the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of the ocean ecosystem. It promotes sustainable fisheries, aquaculture, tourism, and other marine-based industries that can support conservation goals [57].
4. **Rights-Based Approaches:** Indigenous and local communities often have deep connections with marine megafauna. Recognizing and strengthening these communities' rights to manage their local marine resources can be a potent conservation strategy, fostering stewardship and local buy-in [58].

10. ANALYSIS OF THE POTENTIAL BENEFITS AND DRAWBACKS OF THESE STRATEGIES

While these innovative strategies hold great promise, they also come with potential challenges and drawbacks.

1. **Emerging Technologies:** These technologies can enhance data collection

and monitoring capabilities. However, they can also be costly, require specialized skills, and raise privacy and data ownership issues [59].

2. **Climate-Smart Conservation:** This approach allows for more resilient conservation strategies. However, the uncertainty associated with climate change projections can make planning difficult [60].
3. **Sustainable Blue Economy:** While this approach can align economic and conservation goals, it also risks being co-opted to justify exploitative practices without sufficient safeguards [61].
4. **Rights-Based Approaches:** These can empower local communities and foster stewardship, but they also require clear and equitable rights frameworks and can be challenging to implement in contexts with weak governance structures [62].

11. RESEARCH NEEDED TO DEVELOP AND IMPLEMENT THESE STRATEGIES

To advance these strategies, several areas of research are needed:

1. **Interdisciplinary Research:** Developing effective conservation strategies requires an interdisciplinary approach, combining insights from biology, ecology, economics, social sciences, policy, and more.
2. **Policy and Governance Research:** Understanding how to design and implement effective marine governance structures and policies is crucial.
3. **Technological Research:** Continued research into the development and application of conservation technologies is vital, from improving data collection methods to developing new analytical tools.
4. **Community Engagement and Social Research:** Understanding the social and cultural dimensions of marine conservation, including how to effectively engage communities and foster local stewardship, is key.

12. GAPS IN KNOWLEDGE AND FUTURE RESEARCH DIRECTIONS

Despite the significant progress made in understanding and conserving marine megafauna, important gaps in our knowledge remain, hampering the development and implementation of effective conservation strategies (Table 4).

1. **Species-Specific Knowledge:** For many species, basic information about their biology, life history, habitat use, population status, and response to threats is lacking [63]. This paucity of knowledge impedes effective species-specific management and conservation planning.
2. **Socio-Economic Factors:** Understanding the socio-economic factors that drive threats to marine megafauna and influence the success or failure of conservation interventions is critical. However, these aspects are often understudied, leading to conservation strategies that fail to address root causes [64].
3. **Cumulative and Synergistic Threat Impacts:** While individual threats to marine megafauna are often studied in isolation, less is known about the cumulative and synergistic impacts of multiple threats, such as the combined effects of overfishing, habitat loss, and climate change [65].
4. **Long-term Conservation Outcome Evaluation:** The long-term effectiveness of many conservation strategies remains poorly understood, largely due to the lack of long-term monitoring and evaluation [66].

13. FUTURE RESEARCH DIRECTIONS BASED ON THESE GAPS

Addressing these gaps will require concerted research efforts across a range of fields:

1. **Species-Specific Research:** Enhanced efforts to study the biology, ecology, and behavior of marine megafauna are needed. This includes the use of novel technologies such as satellite telemetry and genomics, which can shed new light on aspects like migration patterns, population structure, and adaptation to environmental changes.
2. **Socio-Economic Research:** A greater focus on the social sciences in marine megafauna conservation is required, such as studying the socio-economic drivers of threats and the social impacts of conservation interventions. This includes research on human behavior, economics, policy, and governance.

Table 4. Gaps in knowledge and future research directions for marine megafauna conservation

Knowledge Gaps	Future Research Directions
Species-Specific Knowledge	Enhanced biological, ecological, and behavioral studies on various marine megafauna species using novel technologies
Socio-Economic Factors	Increased focus on socio-economic drivers of threats and impacts of conservation interventions
Cumulative and Synergistic Threat Impacts	Interdisciplinary research and development of holistic ecological models to understand cumulative threats
Long-term Conservation Outcome Evaluation	Investment in long-term monitoring programs and robust evaluation of conservation interventions

3. **Cumulative Impact Assessment:** Future research should aim to better understand the cumulative and synergistic impacts of multiple threats on marine megafauna. This requires interdisciplinary research and the development of more complex and holistic ecological models.
4. **Long-term Monitoring and Evaluation:** Increased investment in long-term monitoring programs and robust evaluation of conservation interventions is critical. This will enable us to learn from past experiences and continually improve conservation strategies.

14. CONCLUSION

Marine megafauna, due to their ecological significance, are vital components of our global biodiversity, and their preservation is paramount. Despite facing numerous challenges, from direct threats like hunting to indirect issues such as climate change, substantial conservation efforts have shown promise. Emerging innovative strategies, leveraging advancements in technology, climate-smart conservation, the sustainable blue economy, and rights-based approaches, offer new avenues for protection. Yet, gaps remain, particularly in understanding species-specific impacts, socio-economic factors, cumulative threats, and long-term conservation outcomes. To address these, future research should focus on interdisciplinary, social, cumulative impact, and long-term monitoring studies, enabling more effective, targeted, and sustainable conservation of these crucial species.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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