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What can marine animal forests do for us?

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ABSTRACT

Marine animal forests (MAFs) are benthic ecosystems dominated by structure-forming invertebrates (e.g., corals, sponges) that provide critical structural habitat and ecosystem services globally. The objective of this paper is to synthesize current knowledge on the role of MAFs in supporting biodiversity, regulating climate, and delivering economic value. Furthermore, it explores how emerging technologies are revolutionizing the study of these ecosystems. The paper concludes by outlining urgent research priorities required to guide conservation efforts and secure the vital services these ecosys

RESUMEN

Los bosques de animales marinos (MAF, por sus siglas en inglés) son ecosistemas bentónicos dominados por invertebrados formadores de estructuras (por ejemplo, corales y esponjas) que proporcionan un hábitat estructural crítico y servicios ecosistémicos a nivel mundial. El objetivo de este artículo es sintetizar los conocimientos actuales sobre la función de los MAF en el mantenimiento de la biodiversidad, la regulación del clima y la generación de valor económico. Además, se explora cómo las tecnologías emergentes están revolucionando el estudio de estos ecosistemas. El artículo concluye esbozando las prioridades de investigación urgentes necesarias para orientar los esfuerzos de conservación y garantizar los servicios vitales que estos ecosistemas proporcionan a la humanidad. tems provide for humanity.

ARTÍCULO CIENTÍFICO

INTRODUCTION

The Core Concept: What is a Marine Animal Forest?

The "Marine Animal Forest" (MAF) concept establishes a functional analogy with terrestrial woodlands (Rossi, 2013). Just as trees dominate a forest on land, MAFs are ecosystems defined by sessile, three-dimensional animals that form complex structures. These underwater "trees" encompass a variety of organisms, including scleractinian corals, gorgonians, sponges, and bryozoans (Rossi et al. 2017a; Orejas et al. 2022) (Fig1).

The forest metaphor is highly appropriate because these foundational species engineer a complex, three-dimensional environment that fundamentally transforms its physical surroundings (Guizien and Ghisaberti 2017; Nelson and Bramanti 2020). This structural complexity generates a vital resource: habitat. The intricate matrix of branches, crevices, and surfaces supplies shelter, nursery areas, and feeding stations for a vast array of associated fauna, from minute crustaceans and fish larvae to large predatory fish and sharks (Buhl-Mortensen et al., 2010). Consequently, MAFs rank among the planet's most biodiverse ecosystems, comparable to tropical rainforests.

"Three-dimensionality" is a key descriptor for ecological complexity (Neves da Rocha et al. 2024). In the ocean, this physical intricacy constitutes the very architecture that supports life. MAFs are quintessential manifestations of this principle. They are not simple aggregations of species but are living, complex matrices that generate a wide spectrum of microhabitats (Cau et al. 2020; Cocozza di Montanara et al. 2025). This architectural diversity is ideally suited to a broad range of marine life, providing countless specialized niches. For example, one coral colony can offer sun-exposed surfaces for symbiotic algae, shaded cavities for cryptic invertebrates, and high-flow areas ideal for filter feeders. Crucially, this physical framework underpins the entire ecosystem's function (Guizien and Ghisaberti 2017), driving essential processes like nutrient cycling, primary production, and energy flow, while also delivering services such as juvenile fish nurseries and protection from predators (Fig2).

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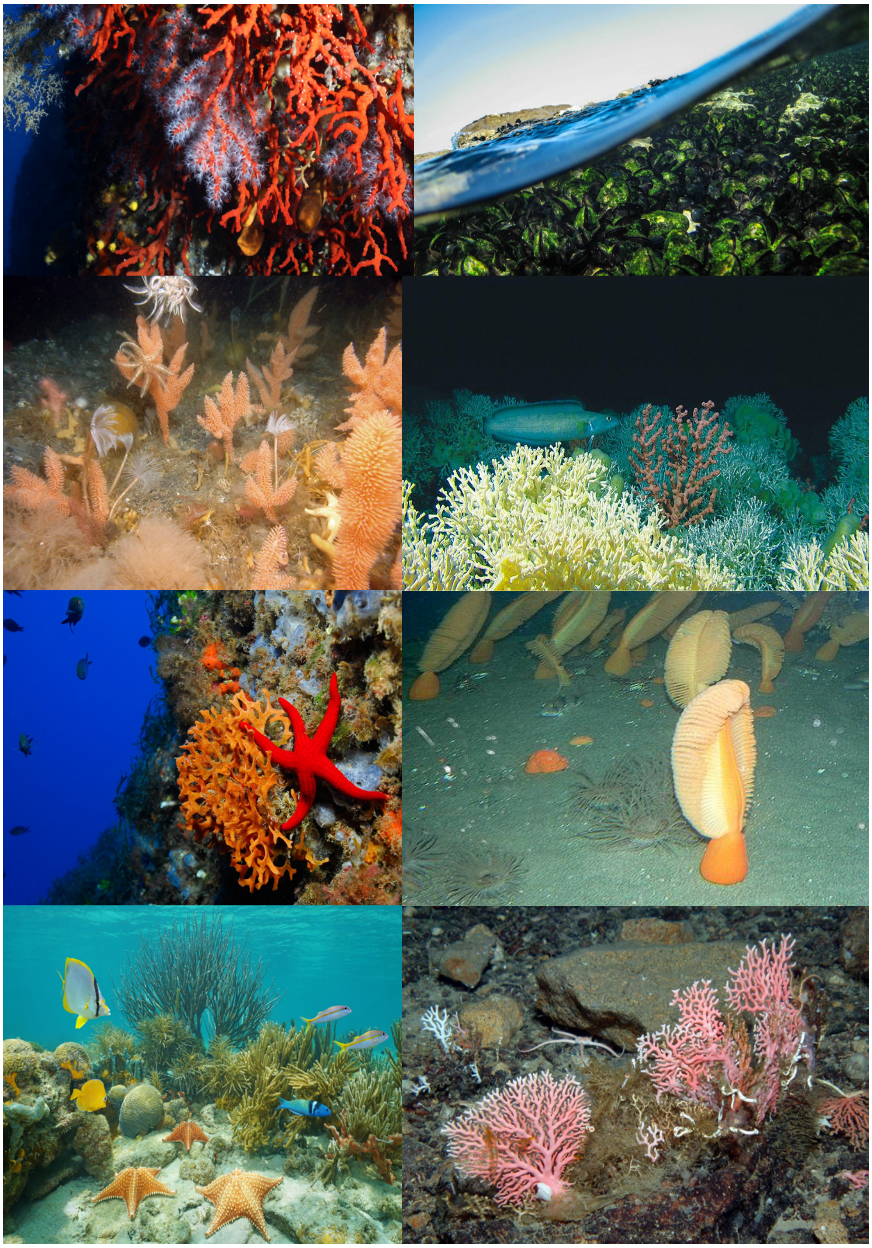

FIGURE 1
Examples of diverse marine animal forests: **(a)** A patch of the precious red coral (*Corallium rubrum*) in the Mediterranean Sea (© ADOBE STOCK). **(b)** A dense mussel bed in the cold North Atlantic (© ADOBE STOCK). **(c)** A lush forest of gorgonians in the icy waters of Antarctica (© AWI-Julian Gutt). **(d)** A deep-sea coral assemblage in a Mediterranean underwater canyon (© ICMGEOMAR). **(e)** A large gorgonian from the biodiverse waters of Indonesia (Irian Jaya) (© ADOBE STOCK). **(f)** The bryozoan *Chartella* sp. creating a delicate structure in the Mediterranean (© ADOBE STOCK). **(g)** A spectacular coral reef in the clear, warm Caribbean Sea (© ADOBE STOCK). **(h)** The Antarctic hydrocoral *Errina antarctica* in the Southern Ocean (© AWI-Julian Gutt).

In contrast, habitats with simpler architecture—such as a monospecific bed of the seagrass *Cymodocea nodosa* or a low-relief mussel (*Mytilus galloprovincialis*) bank—possess significantly lower architectural variety. They offer fewer hiding places and varied surfaces, which results in a less diverse community of associated species, as limited physical space directly equates to fewer ecological niches. Thus, three-dimensional structure serves as a reliable predictor of both biodiversity and ecosystem resilience; complex forests sustain vibrant, interconnected communities, while simpler systems support more limited ones (Orejas et al. 2022).

FIGURE 2
The architectural complexity created by foundational species is directly correlated with increased biodiversity. This complexity supports a rich assemblage of organisms, including both hyperbenthic and epibenthic fauna, which inhabit the structures formed by corals, gorgonians, sponges, and bryozoans. (© Evans-OCEANA).

The foundational process of the MAF is the suspension-feeding strategy of its primary organisms (Gili and Coma 1998). By actively capturing organic particles like plankton and detritus from the water column, they create a crucial energy conduit, transferring nutrients from the pelagic zone to the seabed and sustaining the broader benthic food web (Rossi et al. 2017b) (Fig3). This transfer is fundamental to the ecosystem's productivity. Another key energy source is mixotrophy, where certain bioconstructors, including scleractinians, gorgonians, and sponges, supplement their needs through symbiosis with microalgae (Schubert et al. 2017; Sturaro et al. 2021).

A Multitude of Threats

MAFs are besieged by a devastating array of interconnected threats. The primary stressors originate from climate change (Turner et al. 2023). Ocean warming triggers widespread coral bleaching and mortality by disrupting vital symbioses (Hughes et al. 2018) and places severe metabolic stress on other filter feeders. Simultaneously, ocean acidification, by reducing carbonate ion availability, hinders the skeletal growth of calcifying organisms like corals and sponges (Kroeker et al. 2013). Furthermore, sea-level rise and altered weather patterns can destabilize the precise environmental conditions MAFs require by changing light regimes and sediment dynamics (Hoegh-Guldberg et al. 2018). (Fig 4)

Beyond these global pressures, direct human impacts inflict severe local damage. Nutrient pollution from agriculture and sewage causes eutrophication and algal blooms that smother habitats and degrade water quality (Fabricius 2005). Concurrently, chemical pollutants, including pesticides and heavy metals, introduce toxins that can be lethal or impair reproduction (Negri et al. 2011). The pervasive problem of plastic pollution causes physical harm through entanglement and ingestion, while also leaching chemicals (Lamb et al. 2018; Soares et al. 2020). Mechanically, bottom trawling is one of the most destructive practices, physically demolishing the complex three-dimensional frameworks that took centuries to build (Thrush and Dayton 2002; Rossi 2013; Clark et al. 2016), while even vessel anchoring can cause significant localized damage (Rossi et al. 2021).

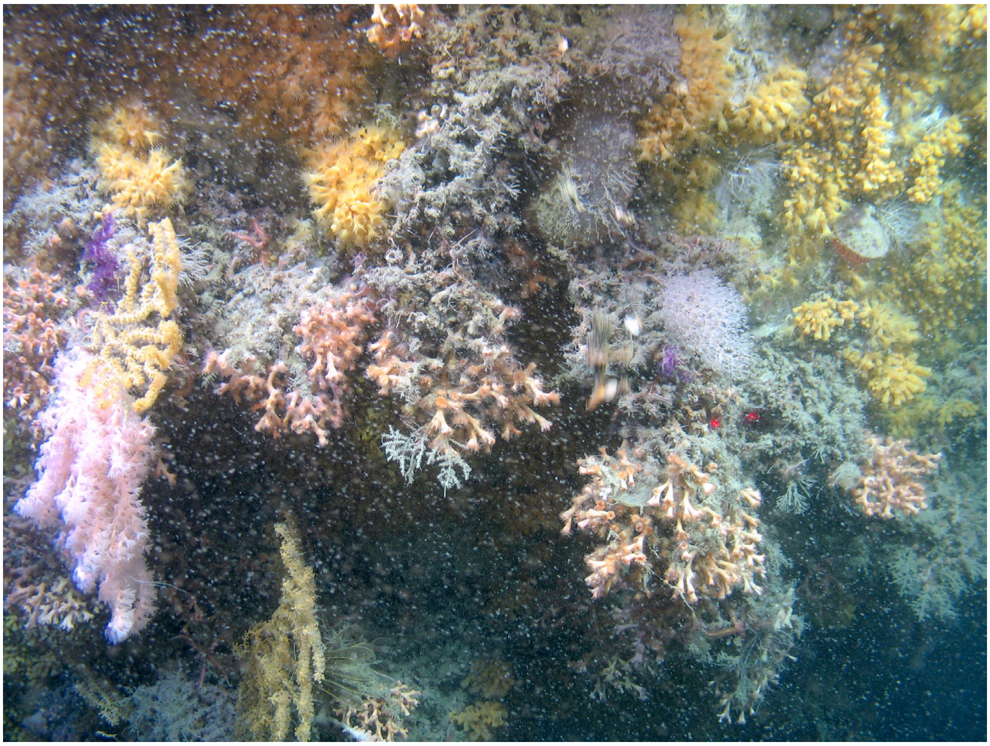

FIGURE 3
Seston—the alive and dead organic matter in suspended particles—provides a constant energy input for benthic suspension feeders. These organisms, whether employing active or passive feeding strategies, possess a wide spectrum of adaptations to efficiently exploit this suspended resource. (© Allcock-NUI Galway)

Other critical pressures include the overharvesting of key species for the aquarium and curio trades, which depletes populations essential to the forest's structure (Tsounis et al. 2010; Jones et al. 2015). Stressed MAFs also exhibit heightened susceptibility to disease outbreaks, which can spread rapidly and cause mass mortality (Weil and Rogers 2011; Weil et al. 2017). Finally, invasive species can disrupt established communities by outcompeting, preying upon, or introducing diseases to native species (Bax et al. 2003; Creed et al. 2021).

The most severe threat emerges from the synergistic effects of these multiple pressures (Thurber et al. 2023). For instance, a reef already weakened by ocean warming becomes far more vulnerable to the impacts of pollution and disease. The cumulative loss of MAFs signifies not only a profound biodiversity crisis but also the failure of essential ecosystem services (Rossi 2013). (Fig 5)

The Benefits of Marine Animal Forests: Ecosystem Services

The extraordinary biological richness of MAFs translates into concrete and intangible benefits for humanity, known as ecosystem services, which can be grouped into four primary categories (Fig 6).

PROVISIONING SERVICES: DIRECT MATERIAL GOODS

Fisheries Production

Marine Animal Forests are fundamental to oceanic productivity and global fisheries. These complex three-dimensional structures serve as essential infrastructure for the life cycles of

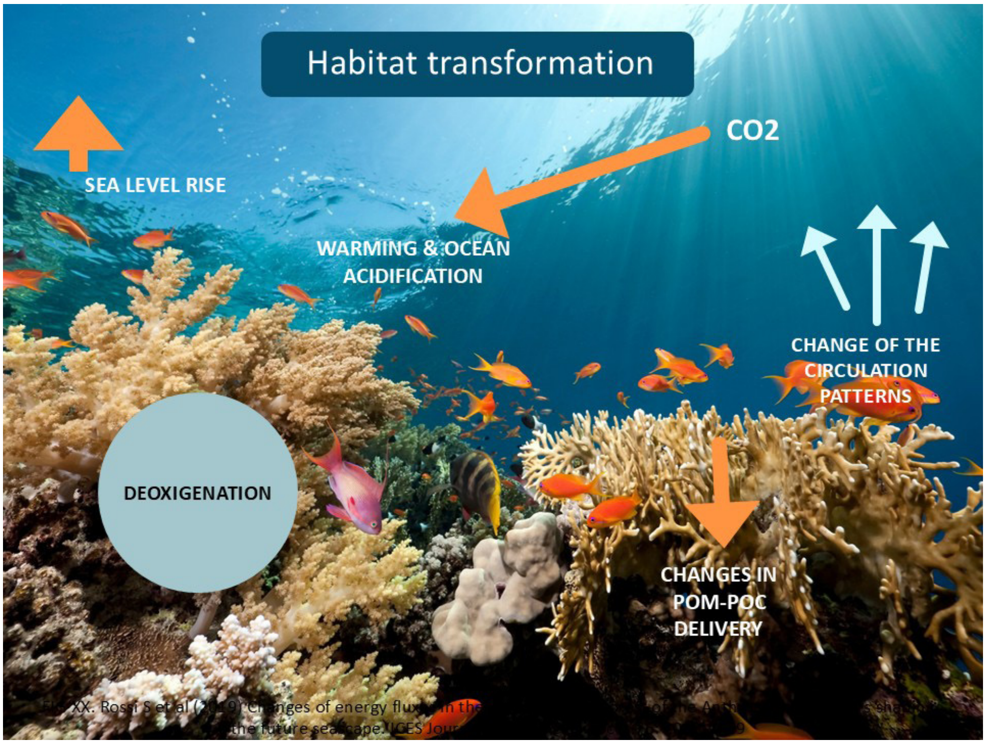

FIGURE 4
The widespread effects of climate change are synergistically impacting Marine Animal Forests globally. The ultimate influence on community survivorship is not uniform; it is modulated by the specific latitudinal and bathymetric (depth) position of each habitat. (© Zorrilla-Pujana)

numerous commercially important species (FAO 2024). They act as critical spawning grounds, vital nurseries offering refuge for juveniles, and productive feeding areas for adults. The structural complexity of a coral reef or sponge garden is directly linked to higher survival rates, as the myriad hiding places protect small fish and crustaceans, greatly improving their chances of reaching maturity (Gratwicke and Speight 2005).The link between MAF health and fishery yield is direct. For example, the valuable Caribbean spiny lobster (*Panulirus argus*) depends on the health of coral reefs and seagrass beds that provide necessary habitat throughout its life cycle (Lipcius et al. 1998). Similarly, in colder waters, fisheries for species like Atlantic cod (*Gadus morhua*) are intrinsically linked to deep-sea coral and sponge grounds, which shelter juveniles and provide a rich feeding environment (Baillon et al. 2012). The FAO consistently emphasizes that the health of the world's most productive fisheries is directly tied to the integrity of coastal ecosystems like MAFs (FAO 2020).

The socio-economic impact is profound. A healthy MAF can sustainably provide protein and livelihoods for local communities for generations. Small-scale fisheries, heavily reliant on these habitats, contribute over half of the global fish catch and employ the vast majority of the world's fishers (Teh and Sumaila 2013). The degradation of a MAF directly triggers a collapse in fisheries production, threatening food security and economic stability in coastal regions.

BIOPROSPECTING

In the ocean's relentless chemical warfare, sessile MAF organisms have evolved a sophisticated arsenal of unique biochemical compounds for defense and competition. This has turned these ecosystems into an unparalleled resource for novel biochemicals with applications in medicine and biotechnology (Avila 2020; Peña and Bárbara 2023).

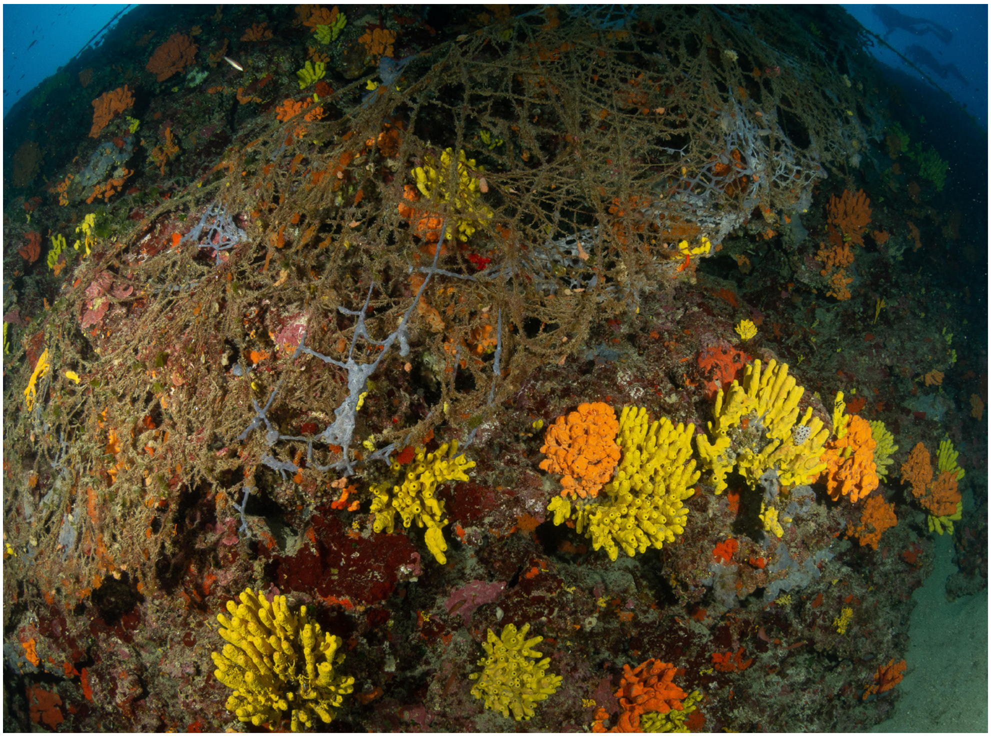

FIGURE 5
Bottom trawling and other fisheries operations drive the profound degradation of Marine Animal Forests through both direct mechanical damage and indirect effects, such as sediment impoverishment and the altered availability of organic matter. (© Thanos)

The potential for discovering life-saving drugs is vast. Sponges, for instance, are metabolic powerhouses, responsible for over 30% of all marine natural products discovered. A landmark example is the Caribbean sponge *Tectitethya crypta*, which yielded nucleosides that became the blueprint for the antiviral drug Vidarabine and the anticancer drug Cytarabine (Ara-C), a cornerstone in leukemia treatment (Leal et al. 2012). The deep-sea sponge *Discodermia dissoluta* provided Discodermolide, a potent anticancer agent with a unique mechanism (Gunasekera et al. 1990).

The search extends to other MAF inhabitants. The bryozoan *Bugula neritina* is the source of Bryostatins, investigated for treating cancer and Alzheimer's (Mutter and Wills 2000). Octocorals produce compounds with remarkable anti-inflammatory properties, used in cosmetics and explored for wound healing (Mayer et al. 2010). This "blue biotechnology" is critical in the face of antibiotic resistance, as marine-derived compounds offer new mechanisms to combat multi-drug resistant pathogens (Indraningrat et al. 2016).

The destruction of MAFs through human activities represents the irreversible loss of unique genetic and biochemical libraries, underscoring that their conservation is a critical investment in global public health.(Fig7)

REGULATING SERVICES: MAINTAINING EARTH'S SYSTEMS

Coastal Protection

MAFs function as self-repairing, dynamic breakwaters. A healthy, complex coral reef can dissipate up to 97% of wave energy before it reaches the shore, significantly reducing wave height and force (Ferrario et al. 2014). This buffering effect is a primary defense against coastal erosion, storm surges, and tropical cyclones.

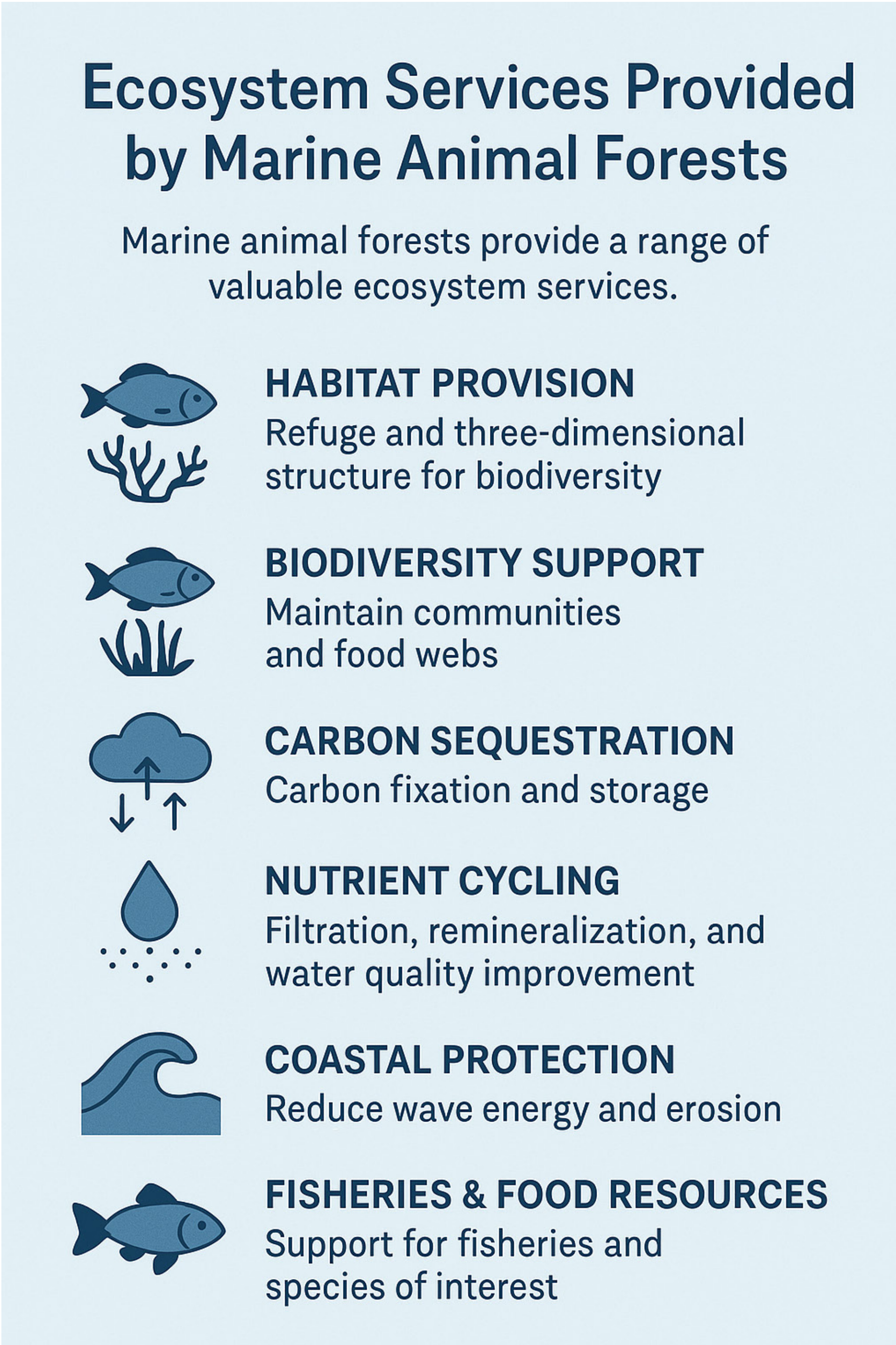

FIGURE 6
Marine Animal Forests (MAFs) are not just beautiful underwater structures; they are critical providers of essential services that benefit both the marine environment and human societies. These services can be grouped into several key categories. (© Rossi)

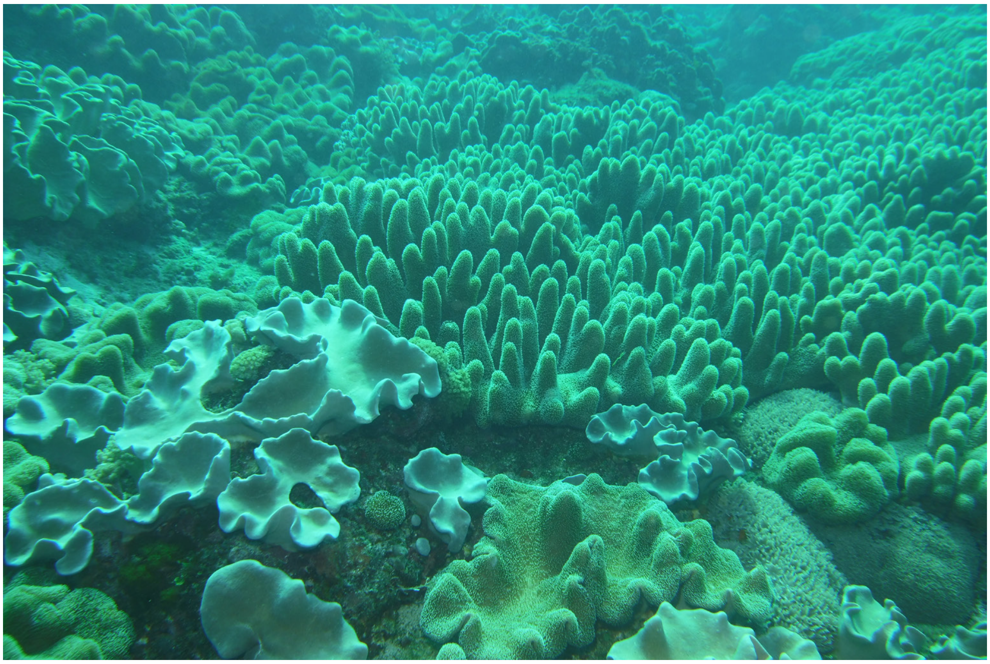

FIGURE 7
A rich source of natural products can be found within the various components of Marine Animal Forests. For example, these soft corals in the Red Sea are known to host a diverse array of bioactive compounds. (© Benayahu)

The protective value is empirically proven. During the 2004 Indian Ocean tsunami, coastlines fronted by healthy mangroves and coral reefs suffered significantly less damage and lower loss of life (Danielsen et al. 2005). The economic argument for conservation is powerful; Florida's coral reefs provide flood protection benefits worth over US$1.1 billion annually (Storlazzi et al. 2019). Globally, coral reefs are estimated to reduce annual flood damages by over US$4 billion (Beck et al. 2018). Preserving MAFs is a cost-effective strategy for climate adaptation and coastal resilience.

Biodiversity and Ecosystem Stability

MAFs are among the most significant biodiversity hotspots on Earth, rivaling tropical rainforests (Rossi et al. 2017a). The complex three-dimensional structures create a multitude of microhabitats and ecological niches that allow thousands of species to coexist by partitioning resources (Bell and Barnes 2003). This phenomenon, where physical complexity directly increases species richness, is a cornerstone of marine ecology (Gratwicke and Speight 2005). Diverse communities are often more resilient to disturbances, and the variety of functional roles ensures the efficient operation of critical processes like nutrient cycling. The loss of these ecosystems signifies an irreversible erosion of planetary biodiversity (Rossi et al. 2022). (Fig8)

Carbon and Nutrient Cycling

MAFs are active players in global biogeochemical cycles. Suspension feeders consume vast quantities of particulate organic carbon (POC), incorporating it into their tissues and skeletons. Deep-sea sponge grounds, for instance, are significant carbon sinks, with sponges assimilating dissolved organic carbon (DOC) into their silica-based skeletons, immobilizing it for centuries (Bell et al. 2021). When these organisms die, their calcium carbonate or silica structures can lock away carbon in deep-sea sediments for geological timescales (Cathalot et al. 2015).

FIGURE 8
The high biodiversity of Marine Animal Forests arises from their complex, mosaic-like structure, which concentrates species with different ecological functions into a small space. In the Mediterranean Coralligene, for instance, the habitat engineered by coralline algae and suspension feeders creates the conditions for a wide array of ephemeral organisms to thrive. (© Rossi)

The three-dimensional structure also acts as an efficient filter, accelerating nutrient recycling. The feeding activity of the community rapidly converts POC into forms available to bacteria and phytoplankton, fueling a localized "bentho-pelagic coupling" (Wild et al. 2011; Rossi et al. 2017b). Cold-water coral reefs, for example, create oases of life in the food-limited deep sea by efficiently capturing and recycling organic matter (van Oevelen et al. 2009). Microbial communities associated with sponges and corals can also supercharge the nitrogen cycle, effectively fertilizing the surrounding waters (Zhang et al. 2015).

Carbon Immobilization and Innovative Models

The role of MAFs as carbon immobilizers is a critical yet understudied component of the global carbon cycle (Langenkämper et al. 2023). While estimates for other "blue carbon" ecosystems exist, there is a stark lack of data quantifying the carbon retained by MAFs (Rossi and Rizzo 2020). Quantifying this sink is essential, as it provides a powerful new rationale for their preservation. (Fig9)

A scalable example is Integrated Multi-Trophic Aquaculture (IMTA), which demonstrates the dual benefit of bioremediation and carbon immobilization. In this model, diverse suspension feeders (e.g., polychaetes, bivalves, sponges) are cultivated near nutrient sources. Research indicates that a single 15-meter vertical rope can support the growth of about 15 kg of fresh animal weight per year, immobilizing approximately 1 kg of carbon. Scaling this up, a 100-meter longline system could sequester about 5 tons of carbon per hectare per year (Arduini et al. 2023; Arduini et al. 2026; Borghese et al. 2025). This cultivated biomass can then be repurposed for biogas, animal feed, or fertilizer, creating a circular economy and framing MAFs as active tools for climate mitigation (Filgueira et al. 2015).

FIGURE 9
Marine Animal Forests contribute to carbon sequestration through the biological activities of their constituent organisms. They immobilize carbon in both inorganic (e.g., calcium carbonate) and organic (e.g., gorgonin) matrices. The timescale of this storage, ranging from short to geological timespans, is determined by the organisms' biological traits and the preservation potential of their skeletal remains. (© Kipston)

Water Filtration and Bioremediation

MAFs function as immense, efficient water purification systems. Dense communities of suspension feeders, such as sponges, bivalves, and ascidians, process colossal volumes of water. A single sponge can filter thousands of liters daily, and entire sponge communities on a reef can filter the overlying water column in a matter of days, controlling plankton and bacterial abundance (Vogel 1977; de Goeij et al. 2013). (Fig10)

This filtration increases water clarity, allowing light to penetrate for photosynthesis, and removes potential pathogens, contributing to a healthier marine environment (Welsh et al. 2017). Furthermore, many MAF organisms are powerful agents of bioremediation:

Bivalve Reefs: Oyster reefs mitigate eutrophication by filtering excess nitrogen and phosphorus from the water (Grizzle et al. 2008).

Sponges: They bioaccumulate heavy metals like copper and lead, sequestering these toxins (Patel et al. 1985).

Ascidians and others: They capture and ingest microplastic particles, helping to mitigate this pervasive pollutant (Renzi et al. 2019; Fraissinet et al. 2024).

CULTURAL SERVICES: NON-MATERIAL BENEFITS

Tourism and Recreation

MAFs are powerful engines for the global tourism economy. Iconic coral reefs attract millions of divers, snorkelers, and wildlife enthusiasts, generating an estimated US$36 billion annually (Spalding et al. 2017). This value translates directly into livelihoods; the Great Barrier Reef

FIGURE 10
Suspension feeders exhibit a wide divergence in their clearance rates. The energy derived from processed particles is channeled into various outputs, including respiration, growth, and reproduction. This is exemplified by these Antarctic sponge grounds, which form a dense patch that efficiently filters a particular size spectrum of particles from the seston. (© AWI-Julian Gutt)

alone supports over 64,000 jobs and contributes Australian Dollars $6.4 billion annually to the Australian economy (Oxford Economics 2017). This model creates a powerful economic incentive for conservation, as a healthy reef directly translates into higher visitor satisfaction and revenue (Brander and Van Beukering 2013).

Scientific, Educational, and Aesthetic Value

MAFs are living laboratories that have advanced our understanding of symbiosis, chemical ecology, and past climate conditions (Gagan et al. 2000; Pawlik 2011). They are dynamic classrooms that foster environmental literacy and inspire future scientists (Guest et al. 2014; Zorrilla-Pujana 2021). Beyond metrics, their breathtaking beauty inspires art and culture and holds deep spiritual significance for coastal indigenous communities, representing an irreplaceable part of our global heritage (Veland et al. 2013; Jimenez and Orejas 2017; Torri 2021). (Fig11)

Supporting Services: The Unseen Foundation

All other services depend on underlying supporting services. The most critical is habitat formation by ecosystem engineers like corals and sponges, who construct the three-dimensional environment itself (Jones et al. 1994). Primary production, driven by symbiotic algae in sunlit waters or water column filtration in deeper areas, provides the foundational energy for the ecosystem (Muscatine and Porter 1977; Buhl-Mortensen et al. 2016). Finally, MAFs act as a global reservoir of biodiversity and genetic library, which is the source of ecosystem resilience and biotechnological potential (Wangensteen and Turon 2016; Worm et al. 2006). These processes are the essential, non-negotiable prerequisites for all other benefits (Orejas and Jimenez 2017; Paoli et al. 2017).

FIGURE 11
A Mediterranean gorgonian exhibiting a surface brooding reproductive strategy. The dynamism and beauty of marine ecosystems are revealed both through their rich biodiversity and through the observation of discrete, seasonal life history events. (© Rossi)

RECENT ADVANCES AND FUTURE DIRECTIONS

Technological innovations are revolutionizing our understanding of MAFs:

Advanced Mapping and Imaging: High-resolution sonar and photogrammetry create detailed 3D "digital twins" for monitoring ecosystem health (Micallef et al. 2012; Price et al. 2019; Gomes-Pereira et al. 2021).

Environmental DNA (eDNA): Sampling water and sequencing the genetic material within it allows for non-invasive biodiversity assessment (Leray & Knowlton, 2015; Jeunen et al. 2023).

'Omics Technologies: Genomics and proteomics reveal the molecular basis of calcification, heat tolerance, and bioactive compound production (Tomanek 2011; van de Water et al. 2022; Quattrini et al. 2023).

Deep-Sea Observatories: Cabled observatories provide a continuous, real-time view into the dynamics of deep-sea MAFs (Orejas et al., 2020).

Unanswered Questions and the Path Forward

Critical knowledge gaps remain that are urgent to address:

Global Extent and Connectivity: Vast areas of the seafloor are unmapped. Understanding how populations are connected by larval dispersal is vital for designing effective marine protected areas.

Quantifying Carbon Sequestration: The precise role of MAFs in the global carbon cycle is poorly constrained. Robust quantification is needed to elevate their importance in climate policy.

Limits of Adaptation: Can MAF organisms adapt quickly enough to survive rapid environmental change? What is the role of their microbiome in resilience?

Cumulative Impacts: Research is needed to understand how multiple stressors (e.g., climate change, pollution, trawling) interact—are their effects additive or synergistic.

Effective Restoration and Mitigation: How can we effectively and scalably restore damaged MAFs, especially in the deep sea

CONCLUSION

Marine Animal Forests are not merely beautiful underwater landscapes; they are foundational pillars of healthy oceans and provide indispensable services to humanity, from food security and climate regulation to medicines and cultural enrichment. The recent technological revolution is finally allowing us to appreciate their true scale, value, and fragility. However, these ecosystems are under unprecedented threat (Duarte et al. 2022). The unanswered questions are not merely academic; they are the roadmap for our survival. Filling these knowledge gaps through dedicated research, coupled with immediate and aggressive policy actions to reduce greenhouse gas emissions and protect critical habitats, is not a choice but a necessity. The fate of the Marine Animal Forest is inextricably linked to our own.

The question "What can marine animal forests do for us?" reveals a profound truth: our fate is inextricably linked to the health of these submerged ecosystems. They protect our shores, feed our populations, cure our diseases, regulate our climate, and enrich our cultures. However, this relationship cannot be one-sided. These forests are under unprecedented threat from pollution, destructive fishing, and the overarching crisis of climate change. The more pertinent question we must now ask is: **What can we do for them?** Protecting, restoring, and sustainably managing marine animal forests is not an act of environmental charity; it is a critical investment in our own security, prosperity, and survival. Their resilience is our resilience (Morris et al. 2023). Their future is our own. (Fig12)

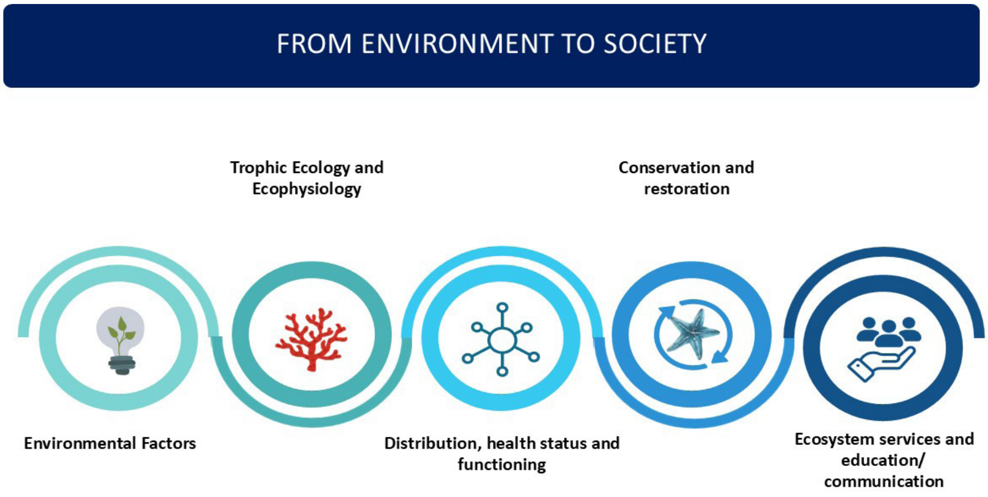

FIGURE 12
Accurately predicting future seascape dynamics requires understanding both shifts in biotic/abiotic factors and their repercussions on the trophic ecology and ecophysiology of benthic suspension feeders. These insights provide a comprehensive outlook on the distribution, functioning, and health of these key organisms. Ultimately, this knowledge is crucial for optimizing conservation and restoration, enhancing natural capital, and providing stakeholders with actionable tools for decision-making, public engagement, and education. (© Zorrilla-Pujana)

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