

The Unsung Heroes of the Deep: Exploring the Crucial Contributions of Sea Spiders (Pantopoda) to the Balance and Diversity of Aquatic Ecosystems.

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Abstract

The Pantopoda, commonly known as sea spiders, has a significant impact on the equilibrium and diversity of aquatic ecosystems. This study elucidates their critical, yet frequently undervalued, roles within these environments. As pivotal predators of sessile invertebrates, sea spiders play a crucial role in regulating prey populations and shaping community dynamics. Their bioturbation activities facilitate enhanced nutrient cycling, and certain species uniquely engage in symbiotic relationships with methanotrophic bacteria, thereby assimilating methane-derived carbon into their tissues. This finding necessitates a reevaluation of marine food webs and has consequential implications for climate science. With over 1300 described species, sea spiders exhibit remarkable diversity across a range of habitats, encompassing both shallow coastal zones and deep-sea ecosystems. Nonetheless, populations of Pantopoda are increasingly threatened by climate change manifested through ocean acidification, elevated water temperatures, and habitat degradation, as well as pollution (including chemical contaminants, plastic debris, eutrophication, and acoustic disturbances) and overfishing practices such as bottom trawling, bycatch, and ensuing trophic cascades. In response, there is an urgent need for the implementation of effective conservation strategies. These should include the establishment of marine protected areas, continued research initiatives aimed at species identification and ecological functions, and assessment of the impacts of climate change. Furthermore, enhanced public awareness and education are paramount. Only through a concerted effort involving scientific inquiry, policy development, and public engagement can we safeguard the long-term viability of these crucial organisms and the health of the marine ecosystems they inhabit.

Keywords: Sea spiders, ecosystem resilience, protected areas, genetic diversity, aquatic ecosystem

Introduction

Aquatic ecosystems represent intricate and dynamic systems that furnish a diverse array of ecosystem services, including provision of food, shelter, and habitat for a multitude of plant and animal species (T, 2024). However, these ecosystems are currently confronting numerous threats, such as climate change,

pollution, and overfishing, which detrimentally affect their ecological balance and diversity (Janshi, Sakariya, & Kamleshbhai, 2023). Sea spiders, classified within the class Pycnogonida, encompass approximately 1500 recognized species distributed across 86 genera. These species exhibit a size range from 0.04 inches to 2.3 feet (Dietz, Dömel, Leese, Lehmann, & Melzer, 2018). They inhabit relatively shallow marine environments, though larger specimens may also be found residing near the ocean floor (Crooker, 2008). Contrary to what their nomenclature implies, sea spiders are not true spiders or arachnids; however, they share a closer phylogenetic relationship with true spiders than with either insects or crustaceans (<https://animalfact.com/sea-spider-pycnogonida/>). Similar to true spiders, sea spiders possess eight legs (P. P. Sharma & Gavish-Regev, 2025).

The anatomical organization of sea spiders exemplifies a distinctive variation within the chelicerate clade, characterized by a suite of lineage-specific traits (Nikolaos Papadopoulos et al., 2025). The prosoma is equipped with a pronounced suctorial apparatus (proboscis), a significantly modified first leg (oviger) employed for egg transportation and grooming, as well as a minimum of four pairs of true walking legs (Arnaud & Bamber, 1988). Notably, three distantly related pycnogonid taxa exhibit the presence of five or six pairs of legs (Ballesteros et al., 2021); (Hedgpeth JW, 1947); (Sabroux, Corbari, & Hassanin, 2023), highlighting the variability in the segmental composition of the prosoma (a characteristic that is atypical among other chelicerate taxa). Pycnogonids exhibit a pronounced reduction of the opisthosoma, which manifests as a diminutive posterior protrusion referred to as the anal tubercle or abdomen (N. Papadopoulos et al., 2025).

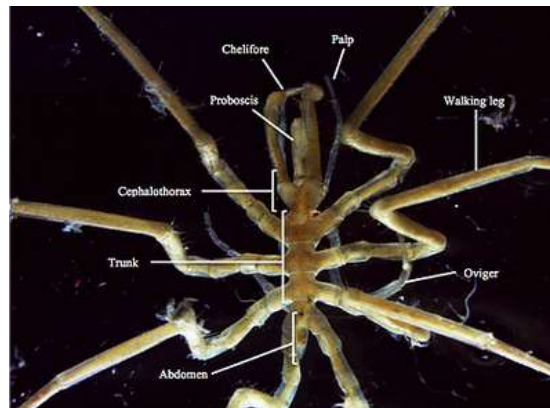


Fig. 1. Sea spider body parts.

It is important to note that the extent to which vestigial opisthosoma segments contribute to the formation of the anal tubercle remains ambiguous (Brenneis, Frankowski, Maaß, & Scholtz, 2023). Despite their distinctive adult morphologies, pycnogonids represent the sole extant chelicerate that exhibit pronounced indirect development. The primary larva, which emerges from the egg, possesses only three appendage-bearing segments and subsequently undergoes anamorph development, characterized by the sequential addition of body segments at the posterior pole (<https://zoology.univie.ac.at/research/marine-invertebrates/pycnogonid-biology-evolution/>). This developmental trait is indicative of the preservation of the ancestral condition observed in both chelicerate and arthropods (Yu Liu et al., 2016); (Wolfe, 2017). Furthermore, sea spiders play an integral role in maintaining the ecological balance and biodiversity of marine ecosystems. They inhabit a diverse range of marine environments, from shallow coastal waters to deep-sea habitats, thereby serving as a critical component of the marine food web (Sophia M, 2024).

This article investigates the significant contributions of sea spiders to aquatic ecosystems, elucidates their remarkable adaptations, and underscores the pressing necessity for heightened awareness and protective

measures to safeguard their continued existence amidst environmental changes. By acknowledging the vital role of these often-overlooked organisms, we can foster a better appreciation for the intricate web of life that underpins marine environments.

Overview of sea spiders

Sea spiders, scientifically classified as pycnogonids within the class Pycnogonida (Sabroux et al., 2023), derive their name from the type genus, Pycnogonum. This assemblage is alternatively referred to as Pantopoda, representing the sole extant order within the class Pycnogonida (Arnaud & Bamber, 1988). While resembling true spiders in both nomenclature and morphology, sea spiders have undergone independent evolutionary pathways (Crooker, 2008). Despite not being classified as true arachnids (arthropods belonging to the class Arachnida), molecular and genetic analyses indicate that pycnogonids may exhibit a closer evolutionary affinity to arachnids than to other arthropod taxa, such as crustaceans or insects (<https://animalfact.com/sea-spider-pycnogonida/>). Notably, they possess chelifores, a distinctive pair of appendages that are homologous to the chelicerae observed in other chelicerate lineages, including spiders and horseshoe crabs (C. Arango, 2018).

Taxonomy and classification

The Pycnogonida (derived from the Greek terms “pyknos,” meaning crowded, and “gony,” meaning knee), commonly referred to as sea spiders, constitute a distinct group of marine arthropods with uncertain phylogenetic affiliations. They are frequently associated with the Chelicerata (Dunlop & Arango, 2005), although this classification remains controversial due to their unique and conspicuous morphological features, which include an external proboscis, a ventral pair of appendages known as ovigers, and a significantly reduced abdomen that manifests as a peg-like vestige (1987). Molecular data have revealed inconsistencies across various analyses, positioning the Pycnogonida either as a sister group to the Chelicerata or as the most primitive lineage among extant arthropods (Giribet, 2000); (Giribet, Edgecombe, & Wheeler, 2001). Recent interpretations of neuroanatomical data suggest a homology between chelifores of sea spiders and the great appendages of Cambrian arthropods, thereby reinforcing the basal position of Pycnogonida (Maxmen, Browne, Martindale, & Giribet, 2005). However, more recent studies on Hox gene expression have provided support for the homology between chelifores and those of other chelicerates (Jager et al., 2006); (Manuel, Jager, Muriene, Clabaut, & Guyader, 2006); (Edgecombe, Wilson, Colgan, Gray, & Cassis, 2000). To date, over 1300 pycnogonid species have been described, with a significant number of additional species anticipated to be discovered, particularly in remote deep-sea habitats (Dudnik & Kremenetskaia, 2025). Taxonomists categorize the known species into approximately 80 genera and eight or nine families, which include Ammotheidae, Austrodecidae, Callipallenidae, Colossendeidae, Nymphonidae, Phoxichilidiidae, Pycnogonidae, Rhynchothoracidae, and Endeididae, a monogeneric family often classified within Phoxichilidiidae. However, phylogenetic studies continue to challenge the monophyly of these families (C. P. Arango & Wheeler, 2007).

Ecologically, pycnogonids, commonly known as sea spiders, are primarily marine benthic inhabitants that inhabit environments ranging from the intertidal zone to abyssal depths across all global seas. Their body sizes exhibit considerable variation, with some species measuring as little as 2 mm in leg span, while others, particularly deep-sea variants, can reach up to 75 cm; larger species are typically associated with deeper habitats (Dudnik & Kremenetskaia, 2025). Sea spiders are predominantly epibenthic and exhibit carnivorous feeding behaviors (Arnaud & Bamber, 1988). Certain species have been documented engaging in parasitic associations with hydroids, molluscs, and echinoderms (Arnaud & Bamber, 1988). Extensive biological and ecological research has been conducted on their feeding and reproductive traits; however, the majority of studies have predominantly focused on temperate or polar species (W. G. Fry, 1965); (de HARO, 2008); (Davenport, Blacstock, & Davies, 1987); see review in (Arnaud & Bamber, 1988). The morphology of sea spiders is characterized by a significantly reduced body structure, often appearing as a mere connector between each pair of legs, resulting in the migration of digestive and reproductive organs

to the legs themselves (Nikolaos Papadopoulos et al., 2025). Most pycnogonid species possess four body segments, each associated with a pair of walking legs. However, certain deep-sea species may exhibit five or six body segments, along with ten or twelve legs, respectively, referred to as polymerous forms (Hedgpeth JW, 1947), a phenomenon that remains unusual among arthropods and warrants further investigation. The first segment, or cephalon, is equipped with an ocular tubercle housing four simple eyes, typically pigmented, as well as the proboscis, the first pair of walking legs, and three additional pairs of appendages: the chelifores located above the proboscis, the palps positioned laterally, and the ovigers found ventrally. The proboscis constitutes the most distinctive external feature of pycnogonids (C. P. Arango, 2001); (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). The proboscis of pycnogonids is a moveable organ exhibiting considerable variability in size and morphology across different families (C. P. Arango, 2001); (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). Researchers have correlated the shape and internal structure of these appendages with the species' specialized feeding behaviors and dietary preferences (W. G. Fry, 1965); (Staples, 1987). The ocular tubercle may present as either a tall, pointed protuberance or a low tubercle situated dorsally along the midline of the cephalon (C. P. Arango, 2001); (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). Notably, certain species, particularly abyssal and psammophilic taxa, may lack the ocular tubercle altogether (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). The chelifores consist of a scale, or proximal segment, and a chela, which features a fixed finger and a moveable finger articulated at the palm (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). In specific species, the fingers may be robust and denticulate, while in others, they appear diminutive and feeble. Chelifores are present throughout all known larval stages and juvenile forms; however, in some taxa, these structures are lost during the final molt preceding adulthood. The palps, presumed homologues to arachnid pedipalps, are multi-segmented appendages that appear to serve sensory, grooming, and feeding functions (Arnaud & Bamber, 1988). It is noteworthy that three families of pycnogonids exhibit a complete absence of palps (Cano-Sánchez & López-González, 2016). The ovigers represent another pair of appendages that are attached to the ventral surface of the cephalon.

Males utilize these appendages to transport eggs until hatching; in some species, they also carry the larvae post-hatching (Crooker, 2008); (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). Ovigers exhibit distinct morphology characterized by a sickle-shaped terminal portion adorned with either denticulate or simple spines (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). Researchers propose that the ovigers are integral to grooming behaviors (Davenport et al., 1987); however, it is plausible that they also fulfill additional critical functions related to mating and parental care. Observations indicate that legs may also serve a cleaning function in both oviger-bearing and non-oviger-bearing pycnogonids. Notably, females of certain taxa lack ovigers, and these structures are entirely absent in all sexes of particular Pycnogonum species (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). The legs of pycnogonids are composed of eight segments and culminate in a prominent distal claw, with many species possessing auxiliary claws located dorsolateral to the main claw. Males are equipped with cement glands on the femora that secrete a substance utilized for the wrapping of eggs and their attachment to the ovigers. The secretion outlet may manifest as a long duct, a short tube, a single pore, or multiple minute pores positioned dorsally or ventrally on the femur (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). Researchers differentiate between male and female pycnogonids by identifying the presence of ovigers in females from certain families and cement glands on the femora in males, while also recognizing the occurrence of hermaphroditic individuals in some species (Miyazaki, 1993). In the reproductive process, females release eggs externally, which males subsequently fertilize and attach to the ovigers in a singular mass (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). This reproductive behavior has been documented in Phoxichilidim femoratum, various species of Endeis (see 1973), Pycnogonum litorale (Jarvis & King, 1972), (Tomaschko, Wilhelm, & Bückmann, 1997), and the mating behavior of *Propallene longiceps* (K.

Nakamura & Sekiguchi, 1980). Among pycnogonids, *Pycnogonum litorale* is the most extensively studied species, particularly noted for its specific associations with hydroids and sea anemones in the North Atlantic (Jarvis & King, 1972); (Behrens, 1984); (Wilhelm, Bückmann, & Tomaschko, 1997); (Tomaschko et al., 1997). The reproductive biology of other species, including *Endeis laevis* (Jarvis & King, 1975), Nymphon species (P. E. King & Jarvis, 1970), and *Parapallene famelica* from the east coast of Australia (Hooper, 1981), has been investigated. Notably, pycnogonids do not undergo a planktonic stage in their life cycle, a characteristic believed to influence their distribution patterns and contribute to a high rate of speciation (Crooker, 2008). In certain callipallenids and nymphonids species, larvae remain attached to the ovigers of the parent until they reach a well-developed stage, specifically after the fourth instar (Koichiro Nakamura, 1981). Pycnogonid protonymphs exhibit morphological similarities to the nauplius larva of crustaceans; however, they possess a proboscis, exhibit chelifores equipped with robust pincers, and have two additional pairs of appendages, each bearing a single terminal claw (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). The taxonomy of Pycnogonida is primarily predicated on the presence and the characteristics of the appendages associated with the cephalic segment. Specifically, the morphology of chelifores, palps, and ovigers, including their presence, segment number, and configuration, serves as the basis for the artificial classification of families currently employed in the field (<https://www.australasian-arachnology.org/arachnology/pycnogonida/>). Notable early contributions to Pycnogonida taxonomy include monographs (Hoek, 1881); (Loman, 1908), alongside more recent works (Hedgpeth JW, 1947); (Joel Walker Hedgpeth, 1954); (Jan H. Stock, 1975); (Jan H. Stock, 1994). Reviews of this taxonomic group have been conducted (Helfer, 1935), (Fage, 1949), (P. E. King, 1973) and (Arnaud & Bamber, 1988), providing thorough reports on species from specific geographical locations. Furthermore, researchers such as (Gordon, 1944); (J. W Hedgpeth, 1948); (J. W Hedgpeth, 1949); (J. H Stock, 1954); (W. G. H. Fry, J. W, 1969) have made significant contributions to the literature through their respective studies, advancing our understanding of this diverse group.



Fig. 2. Sea Spider classification

The majority of published research has predominantly concentrated on the taxonomy and general biology of Pycnogonida. However, recent contributions by researchers such as (Mercier & Hamel, 1994), (C. Arango & Brodie, 2003), (Sherwood, Walls, & Ritz, 1998), (C. Arango, 2001) have yielded novel insights into the ecology of specific species. In contrast, the phylogenetic relationships within Pycnogonida remain inadequately explored. (Hedgpeth JW, 1947) established a classification system grounded in traditional morphological distinctions. Most students of the group currently accept and follow this classification, which continues to be widely accepted by contemporary scholars, with minimal modifications. This classification is underpinned by a hypothesis proposing a reduction series in the number of segments as an evolutionary trend associated with the loss of appendages (Hedgpeth JW, 1947); (Jan H. Stock, 1994). While this hypothesis has provided a straightforward explanation for the phylogenetic framework of the group, it is imperative to develop methodologies that can rigorously test this taxonomic assertion. Current analytical techniques for morphological and molecular data present an opportunity to rigorously evaluate the hypothesis of gradual reduction and to explore alternative narratives regarding the evolutionary history of sea spiders.

Physical characteristics

Sea spiders, belonging to the class Pycnogonida, typically exhibit a leg span ranging from 0.1 cm to 50 cm (0.04 to 20 in) when fully extended, a variation influenced by their geographical distribution (Crooker, 2008). Notably, certain species inhabiting polar regions, such as a member of the genus *Colossendeis* from Antarctica, can attain a leg span of up to 70 cm (27 inches) (<https://www.animalfact.com/sea-spider->

[pycnogonida/](https://www.marinespecies.org/pycnobase/)). These arthropods are characterized by slender, jointed appendages that extend along their body. Most species possess four pairs of legs, a trait that is also observed in the majority of terrestrial arachnids. However, families such as Pycnogonidae, Colossendeidae, and Nymphonidae may exhibit a polymorous condition, possessing five to six pairs of legs (<https://www.marinespecies.org/pycnobase/>). Taxonomists have classified nine species into two primary groups: seven species with five pairs of legs are allocated to four genera (Decolopoda, Pentacolossendeis, Pentapycnon, and Pentanymphon), while two species with six pairs of legs are assigned to distinct genera, Dodecolopoda and Sexanymphon (<https://animalfact.com/sea-spider-pycnogonida/>). Despite the absence of clearly defined segmentation, researchers recognize broad divisions within the body structure of sea spiders. The anterior region, referred to as the cephalon, is composed of a straw-like proboscis, an ocular tubercle, and four pairs of appendages, which include, sequentially, the chelifores, palps, ovigers, and the first pair of walking legs (<https://animalfact.com/sea-spider-pycnogonida/>).

The vital organs of Pycnogonida, such as the intestines, extend into their appendages due to their markedly reduced central body cavity. Observations indicate that both the cephalothorax and abdomen are significantly diminished, with the abdominal segment having lost its appendages, rendering it functionally vestigial. Notably, sea spiders do not possess lungs; instead, respiratory functions are facilitated through the exoskeleton of their legs, where hemolymph circulates to transport oxygen throughout the organism. Distinctive among arthropods, the process of gut peristalsis, a series of muscular contractions within the digestive tract, extends into the legs, thereby facilitating the circulation of hemolymph within those appendages. The circulatory system of a sea spider is characterized as open, featuring a small heart that beats rapidly to pump hemolymph through the trunk and proximal regions, while the gut actively aids in driving circulation to the distal regions (<https://animalfact.com/sea-spider-pycnogonida/>). Current research into the excretory mechanisms of sea spiders remains limited; however, it is hypothesized that diffusion serves as the primary mode of waste excretion in these organisms. A primitive excretory organ, comparable in length to the scape of the chelifores, has been documented in *Nymphopsis spinosissima*. This organ comprises an end sac, a proximal tubule, a distal tubule, and a nephropore (<https://invertebrate.us/all-about-sea-spiders-pycnogonida/>). The nervous system of sea spiders consists of a dorsal brain, referred to as the supraesophageal ganglion, alongside a pair of ventral nerve cords that extend along the body and give rise to accessory nerves responsible for innervating the limbs and other anatomical structures (Crooker, 2008); (<https://animalfact.com/sea-spider-pycnogonida/>). All species of sea spiders are characterized as gonochoric, exhibiting separate sexes, with the exception of *Ascorhynchus corderoi*, which is a hermaphrodite possessing both testes and ovaries within a single individual. The reproductive process involves external fertilization, wherein the male mounts the female for copulation. Following this, the female releases her eggs, which are subsequently fertilized externally by the male's sperm. Post-fertilization, the male sea spider employs cement glands to attach the egg clusters to his ovigers, carrying them until hatching occurs. The duration of the hatching period varies among species, typically ranging from several days to approximately one month. Each larva is characterized by the presence of a head and three pairs of cephalic appendages (chelifores, palps, and ovigers), while the development of thoracic and abdominal appendages occurs in subsequent stages (<https://animalfact.com/sea-spider-pycnogonida/>). Researchers have identified a minimum of four distinct larvae types within the class Pycnogonida. The typical protonymph larva represents the most prevalent free-living form, gradually maturing into adulthood. In contrast, the encysted larva exhibits a parasitic lifestyle, burrowing into colonies of cnidarians and mollusks, and remains in a cystic state until it reaches the juvenile phase. The attaching larva, resembling an embryo due to its undeveloped limbs, adheres to the male's ovigers immediately following hatching. Additionally, the atypical protonymph larva inhabits or resides within temporary hosts such as polychaetes and clams (Bain, 2003). The coloration observed in sea spiders displays considerable variability across species, encompassing shades of brown, beige, orange, and even vibrant hues, which frequently facilitate camouflage within their respective habitats (Crooker, 2008).

Habitat distribution

Researchers have established that sea spiders exhibit a cosmopolitan distribution, inhabiting all global oceans (Scientists Discover Amazing Abilities in Sea Spiders). Their investigations have predominantly focused on the Pacific waters surrounding the United States and Japan, with significant occurrences also documented in the Caribbean and Mediterranean seas, as well as the coastal waters of South Africa, Australia, and New Zealand (Romero, 2024). Furthermore, sea spiders extend their range to Antarctica, which is home to nearly 20% of the world's sea spider species. Despite the extreme conditions prevalent in polar regions, these organisms demonstrate remarkable diversity, inhabiting the seafloors beneath sea ice. In this environment, they effectively camouflage against sandy substrates and benthic algae, thereby enhancing their evasion of predators. Additionally, they frequently engage in commensal associations with cnidarians, including sea anemones and hydroids. By adhering to these hosts, sea spiders are able to passively transport themselves to new locations, potentially augmenting their access to food and shelter (<https://animalfact.com/sea-spider-pycnogonida/>).

Ecological role of sea spiders

1. Predatory behavior

Benthic fish, including sculpins and flatfish, exhibit predatory behavior towards smaller sea spider species and juveniles (Sea Spiders - Facts, Size, Habitat, Diet, Types, & Pictures). Researchers have documented interactions between shorebirds such as gulls (*Larus spp.*) and sandpipers (*Calidris spp.*) that forage for sea spiders on exposed flats during low tide within the intertidal zone. Additionally, rays and skates, particularly species within the genus *Raja*, are known to consume sea spiders while foraging for benthic invertebrates in subtidal sandy habitats (<https://www.montereybayaquarium.org/animals/animals-a-to-z/sea-spider>).

2. Prey dynamics

Most species of Pycnogonida predominantly consume soft-bodied invertebrates, including cnidarians, sponges, polychaete worms, and bryozoans (Dietz et al., 2018). They employ their elongated, tubular proboscis to penetrate the tissues of their prey, facilitating the extraction of internal fluids. In most instances, this feeding behavior culminates in the mortality of the prey, thereby categorizing the sea spider as a predator (What Do Sea Spiders Eat? Their Diet & Feeding Habits - Biology Insights). However, a notable exception exists in their interaction with sea anemones. Sea spiders exhibit the ability to extract fluids from sea anemones repeatedly without inducing mortality, which reclassifies their relationship with these organisms as parasitic rather than predatory (Dietz et al., 2018).

3. Nutrient cycling

The locomotion of sea spiders within and across sedimentary matrices, a phenomenon known as bioturbation, facilitates the aeration of the upper layers of the benthic environment (Tarhan et al., 2025). This mild disturbance enhances microbial activity by promoting the mixing of organic matter and dissolved oxygen, thereby accelerating the decomposition process and the subsequent release of essential nutrients, including nitrogen and phosphorus, into the water column. Furthermore, sea spiders excrete metabolic waste products, such as ammonium (NH_4^+), directly into the aquatic environment. Ammonium represents a highly bioavailable form of nitrogen, readily assimilated by primary producers, including phytoplankton and algae, thus effectively "recycling" this nutrient back into the foundational levels of the food web.

Research has documented the presence of sea spiders within the genus *Sericosura* exclusively in chemosynthetic habitats, including hydrothermal vents, methane seeps, and whale falls (Bamber, 2009); (Bravo, Mueller, Arango, Tigreros, & Melzer, 2009). This distribution suggests a potential reliance on the high-energy chemical compounds prevalent in these environments. Notably, a distinctive symbiotic

relationship exists between Sericosura sea spiders and epibiotic methane-oxidizing bacteria (Dal Bó et al., 2025). These spiders, located at methane seeps along the Pacific margin, harbor diverse methylophilic bacterial communities on their exoskeletons, which they cultivate and subsequently consume. Evidence derived from tissue isotopic analysis, microbiome sequencing, and live-animal incubations employing ^{13}C -methane isotope probing substantiates the active incorporation of methane-derived carbon into spider tissues (Dal Bó et al., 2025; Hojo, 2022). Furthermore, methane has been recognized as a potentially significant source of carbon and energy for lacustrine food webs, particularly through grazing by detritivorous arthropods on sediment methanotrophs (Deines, Bodelier, & Eller, 2007); (Dietz et al., 2018). In contrast to these arthropods, Sericosura sea spiders appear to directly cultivate and consume their associated methane-oxidizing bacterial community from their bodies, rather than sourcing these bacteria from abiotic surfaces. This behavior indicates their potential to establish novel associations with methane-cycling microbes (Hoban et al., 2022).

Biodiversity and sea spiders

In a seminal discovery that challenges existing paradigms concerning marine ecosystems, researchers have identified three novel species of sea spiders inhabiting the aphotic zones of the ocean, subsisting on methane-oxidizing microbes (Dal Bó et al., 2025). This finding elucidates a unique symbiotic relationship with potentially profound implications for climate science. The presence of sea spiders enhances the biodiversity of reef ecosystems, thereby contributing to the complex web of biotic interactions that underpin the overall health and resilience of these marine habitats.

a. Species diversity

Sea spiders exhibit remarkable species diversity, with over 1,300 formally described species (Maxwell et al., 2022). Their distribution spans both polar and tropical regions, encompassing a variety of environments, including coral reefs, deep-sea benthic zones, and intertidal areas (Sea spider | Animals | Monterey Bay Aquarium). These species demonstrate a wide array of morphological adaptations, characterized by variations in size, leg length, body shape, and coloration. For example, Arctic sea spiders tend to be larger, whereas species residing in tropical regions are generally smaller and exhibit more vibrant coloration (Mathewson, 2016). Different species of sea spiders occupy distinct ecological niches and often engage in predation on various invertebrates, such as sea anemones, sponges, and barnacles (Dietz et al., 2018). This predatory behavior plays a crucial role in maintaining the balance of marine ecosystems and influencing species interactions. Furthermore, certain sea spider species exhibit specialization for specific habitats; for instance, some are adapted to the deep-sea environment, while others thrive in intertidal zones. Such specialization contributes to increased species diversity, as distinct species adapt to specific environmental conditions. Sea spiders exhibit a global distribution across the world's oceans; however, their species' diversity is regionally variable. Polar regions harbor a higher concentration of species, attributable to the cold-water adaptations essential for survival, whereas tropical areas support a different assemblage of adapted species. Despite this diversity, numerous sea spider species face threats from anthropogenic activities, including overfishing, climate change, and habitat degradation (Branco & Cardoso, 2020). Understanding species diversity is paramount for conservation initiatives, as it can inform strategies aimed at safeguarding vulnerable species and their habitats. The classification and description of sea spider species present challenges due to morphological similarities among certain taxa. This complexity underscores the necessity for molecular studies and genetic analysis to elucidate cryptic species and enhance our comprehension of species diversity.

b. Genetic diversity

Genetic diversity encompasses the range of genetic variation present within individual organisms of a single species (Nonić & Šijačić-Nikolić, 2019); (Salgotra & Chauhan, 2023). This aspect of biodiversity is essential for the survival and adaptability of populations, as elevated genetic diversity confers increased

resilience to environmental fluctuations, susceptibility to disease, and reproductive success (Hoban et al., 2022). Furthermore, the genetic diversity serves as a reservoir of phenotypic traits that may prove advantageous in response to altered ecological conditions. For sea spiders, populations exhibiting heightened genetic variability may exhibit enhanced capacity to endure changes in temperature, salinity, and habitat availability. Over evolutionary time scales, natural selection may preferentially act upon individuals possessing advantageous traits, thereby facilitating evolutionary adaptations within the population (Birader, 2023b). As marine ecosystems increasingly confront stressors associated with climate change, pollution, and habitat degradation, the role of genetic diversity becomes paramount in determining the capacity of sea spider populations to adapt to such challenges (Rilov et al., 2019). Populations characterized by low genetic diversity are likely to experience a heightened difficulty in surviving rapid environmental changes and increased disease prevalence. In contrast, those with greater genetic variability may demonstrate enhanced adaptive potential (Jump, Marchant, & Peñuelas, 2009). Moreover, sea spiders engage in complex interactions with a multitude of marine organisms, fulfilling critical ecological functions as both predators and prey within their respective ecosystems. The genetic diversity within sea spider populations can significantly influence their ecological roles, potentially shaping food web dynamics and overall ecosystem health. Populations possessing robust genetic diversity are better equipped to exploit a variety of ecological niches, thereby promoting stable community structures and interactions.

c. Ecosystem resilience

Ecosystem resilience is defined as the capacity of an ecosystem to absorb disturbances and reorganize while undergoing transformation (Arreguín-Sánchez, 2022). Resilient ecosystems sustain their fundamental functions and services in the face of external pressures, thereby serving as crucial components for human well-being and the overall health of the planet. Elevated species diversity promotes a plethora of interactions among organisms, including predation, competition, mutualism, and parasitism (Bachelot, Uriarte, & McGuire, 2015). These interactions establish a complex web of relationships that enhance ecological stability. In this context, sea spiders (Pycnogonida) play a significant role as predators, contributing to the equilibrium of invertebrate populations within their ecosystems, and thereby bolstering community stability and resilience (Unveiling the mysteries of sea spiders: their role and importance in marine ecosystems - The National). By preying on soft-bodied invertebrates such as sea anemones, sponges, and coral polyps, sea spiders fulfill essential functions in nutrient cycling and energy transfer (Crooker, 2008). This functional role is critical for maintaining the health and productivity of marine ecosystems, particularly within benthic habitats. Furthermore, genetic diversity within sea spider populations enhances their adaptive capacity to environmental fluctuations (Aagaard et al., 2022). A population characterized by a broad spectrum of genetic traits is more likely to endure challenges such as climate change, habitat modification, or disease outbreaks (Birader, 2023a). Such adaptable populations contribute to ecosystem resilience by preserving stable predator-prey dynamics and facilitating recovery following disturbances (Thorogood et al., 2023). Ecosystems characterized by high biodiversity exhibit greater resilience to stressors such as pollution, habitat degradation, and climate change (Davila, 2025). Sea spiders, possessing both genetic and species diversity, are capable of responding more effectively to environmental shifts. For example, distinct sea spider species may demonstrate varying tolerances to temperature fluctuations and ocean acidification, thereby providing a buffering effect for the overall ecosystem against rapid environmental changes. Sea spiders are integral components of marine food webs (Andriuzzi, 2025). As predators that consume a diverse array of invertebrates, they significantly influence population dynamics and species composition within the benthic community. Their presence can regulate the populations of prey species, thereby indirectly supporting the broader spectrum of species that interact with these prey. The maintenance of healthy food web relationships is essential for enhancing ecosystem stability and resilience. Moreover, the feeding behavior of sea spiders, characterized by their predation on benthic organisms, contributes to nutrient cycling within the ecosystem. By modulating the populations of grazers and decomposers, sea spiders play a vital role in sustaining the equilibrium of nutrients in their environment.

This regulatory function underpins overall productivity and stability, both of which are crucial for ecosystem resilience.

Interaction with other marine organisms

a. Symbiotic relationships

Symbiosis is defined as the interaction between two distinct biological species engaged in a close association, which can manifest in various forms. These interactions can be classified into three primary categories: mutualism, commensalism, and parasitism, based on the benefits and detriments experienced by each organism involved (Parniske, 2000). A comprehensive understanding of these relationships is crucial for elucidating the ecological roles of sea spiders (class Pycnogonida) and their significance within marine ecosystems.

In mutualistic relationships, both organisms derive benefits from the interaction (Hojo, 2022). Although mutualistic interactions involving sea spiders are less extensively documented compared to those of other marine organisms, certain species may engage in beneficial associations. Some sea spiders form associations with benthic organisms, such as soft corals or sponges. In these interactions, sea spiders may gain shelter while simultaneously aiding in the regulation of their hosts' prey populations (Dal Bó et al., 2025). For example, by feeding on invertebrates or other small organisms associated with corals, sea spiders contribute to the maintenance of a healthy ecological balance, ultimately benefiting the coral by mitigating competition for resources.

In commensal relationships, one organism benefits while the other remains neither helped nor harmed (Hulme-Beaman, Dobney, Cucchi, & Searle, 2016). Sea spiders exhibit commensal behavior with a variety of marine hosts (<https://animalfact.com/sea-spider-pycnogonida/>). They may inhabit or attach themselves to larger organisms such as corals, sea urchins, or sponges (Crooker, 2008). Through this association, sea spiders acquire a protective environment that enhances their ability to evade predators. The host organisms remain unaffected, thereby allowing the sea spider to benefit without imposing significant costs on the host. Certain sea spiders inhabit the surfaces of larger organisms, particularly in complex environments where they can find refuge. This relationship frequently affords the sea spider protection from predation and mitigates exposure to environmental stressors.

(Olano, Weller, & Guerrant, 2011) define parasitic relationships as those in which one organism benefits at the expense of another. Although sea spiders are not typically classified as parasites in the traditional sense of feeding off their hosts, researchers have observed that they actively engage in parasitic interactions with certain organisms. Sea spiders utilize a specialized proboscis to extract fluids from soft-bodied invertebrates, including sea anemones, sponges, and soft corals (<https://animalfact.com/sea-spider-pycnogonida/>). While this feeding behavior does not strictly meet the criteria for parasitism, it resembles parasitic feeding, as it can compromise the health of the host organism by depleting vital nutrients (Staples DA, 2005). The detrimental effects on the host, however, are contingent upon the host's capacity to endure such feeding. Sea spiders primarily prey on various small marine invertebrates, thereby assuming the role of predator (<https://www.aquariumkeeping.co.uk/reef-keeping/sea-spiders-the-creepy-crawlers-of-the-reef/>). This predatory behavior contributes to the regulation of prey populations within ecosystems, thereby influencing food web dynamics and species interactions. Additionally, some sea spiders establish relationships with small marine invertebrates that inhabit or associate with them. By preying on these smaller organisms residing in proximity to their hosts, sea spiders indirectly benefit their host species by reducing competition for space and resources.

b. Competition with other species

Competition is a fundamental ecological interaction that arises when two or more species contend for the same limited resources, including food, space, and habitat (Begon & Harper, 1996). In marine ecosystems,

competition can profoundly influence species distributions, population dynamics, and community structures. It manifests primarily in two forms: intraspecific competition (between members of the same species) and interspecific competition (between different species) (Anupama Sapkota, 2023). This discussion centers on the competitive interactions of sea spiders (class Pycnogonida) with other marine organisms. Within sea spider populations, individuals may compete for limited resources, such as food and space. Given that many sea spider species inhabit analogous benthic environments, competition can significantly impact growth, reproduction success, and overall fitness. Sea spiders primarily feed on soft-bodied invertebrates, such as anemones, sponges, and small crustaceans. When multiple sea spider individuals co-occupy the same habitat, they may compete for these food resources, potentially resulting in modifications to feeding behaviors or shifts in distribution patterns. Furthermore, sea spiders frequently inhabit specific microhabitats, such as crevices within coral reefs or on the surfaces of sponges and other invertebrates, which may further intensify competitive interactions.

Limited spatial availability can precipitate competition for optimal locations to settle, thereby influencing survival and reproductive success. Sea spiders also engage in competitive interactions with other marine organisms for resources within shared habitats. This competition encompasses a diversity of species, including other predators and herbivores that possess overlapping dietary preferences. As opportunistic feeders, sea spiders share the prey community with various benthic predators. For instance, they may compete with small fish, crabs, or other invertebrates that also target slow-moving or sessile prey, such as soft corals and sponges (Dietz et al., 2018). This competitive dynamic can result in fluctuations in the population sizes of both sea spiders and their competitors, contingent upon prey availability. To mitigate competition, different species of sea spiders or distinct life stages of the same species may occupy specialized niches within the ecosystem. These organisms may exhibit variations in dietary preferences based on the size or type of prey consumed, thereby facilitating coexistence without direct competition for identical food sources (Andriuzzi, 2025). Elevated levels of competition can restrict food availability for sea spiders, leading to diminished growth rates, reduced reproductive output, and compromised survival (Chen, Tang, Zhao, Wu, & Huang, 2016). Such dynamics may affect the overall population density of sea spiders within specific habitats, potentially resulting in local declines or alterations in community structure. In response to competitive pressure, sea spiders may develop behavioral adaptations, such as modifying foraging strategies or habitat utilization. For example, in the event of increased competition for a particular prey item, sea spiders might diversify their diet to include less prevalent prey or explore alternative foraging areas. Intense competition with other species can profoundly influence the overall biodiversity of a habitat. If sea spiders or their competitors contribute to the local extinction or decline of specific prey species, this may have cascading effects on the entire community structure, impacting not only the sea spiders themselves but also other associated marine organisms.

c. Impact on food web

A food web constitutes a complex network of trophic interactions among organisms within an ecosystem (Fontefrancesco & Sidsaph, 2019). It elucidates the flow of energy and nutrients through various trophic levels, from primary producers to herbivores and apex predators. A comprehensive understanding of food web dynamics is essential for elucidating ecological balance and the functional roles of diverse species, including sea spiders (class Pycnogonida), which fulfill significant ecological roles within marine ecosystems. Sea spiders inhabit multiple trophic levels within the food web, primarily acting as predators (Dietz et al., 2018). They predominantly consume soft-bodied marine invertebrates such as sea anemones, sponges, mollusks, and small crustaceans. As opportunistic feeders, their dietary preferences may fluctuate in response to variations in food availability, rendering them adaptable constituents of their ecosystems. By preying on various small benthic invertebrates, sea spiders contribute to the regulation of these populations, thereby influencing community dynamics within their habitats. This predation serves to prevent any single species from attaining excessive dominance, thereby facilitating greater diversity within the benthic community. The feeding behavior of sea spiders significantly influences the relative success and decline of

various species within a habitat (Dietz et al., 2018). When a sea spider preferentially targets a specific prey species, this behavior can precipitate shifts in species composition and abundance, ultimately affecting overall community dynamics. By preying upon particular species of benthic invertebrates, sea spiders indirectly modulate competition among other organisms. For example, a decline in the population density of a more competitively advantageous prey species may enable less competitive species to proliferate, thereby enhancing biodiversity within the habitat. As predators, sea spiders play a crucial role in nutrient cycling within their ecosystems. The decomposition of their prey, once consumed, contributes to the nutrient pool, which supports the growth of microorganisms and primary producers, such as algae and sea grasses. Additionally, sea spiders share their feeding niche with other marine invertebrates and small fish that exploit similar food resources, further illustrating the interconnectedness of trophic interactions within marine ecosystems. The competition and interactions among species can significantly shape the structure of the food web; fluctuations in sea spider populations can create cascading effects throughout the web, thereby influencing the abundance and behavior of other predator species. The presence of sea spiders may alter the foraging strategies employed by other predators (S. Liu et al., 2015). For instance, if sea spiders efficiently exploit specific prey, other predators may adapt their feeding behaviors in response, resulting in indirect effects that reverberate throughout the food web. As predators, sea spiders exhibit heightened sensitivity to alterations in environmental conditions, including temperature variations, ocean acidification, and the availability of prey species (Hu et al., 2024). Variation in sea spider populations can compromise the stability and resilience, leading to broader ecological ramifications. Anthropogenic activities, such as overfishing and habitat modification, may precipitate declines in both sea spider populations and their prey. Such changes can destabilize food webs, diminish species diversity, and adversely affect the overall health of marine ecosystems. Sea spiders are recognized as bioindicators of marine ecosystem health due to their sensitivity to environmental fluctuations (De, Siliwal, Uniyal, & Hussain, 2022). Monitoring their populations can yield valuable insights into the status of the food web and the broader dynamics of the habitat.

Threats to sea spider populations

In coastal continental-shelf regions, characterized by depths ranging from approximately 20 meters to 200 meters, bottom trawling operations utilize nets that indiscriminately sweep the seafloor, resulting in significant bycatch of various organisms. Sea spiders (Pycnogonida), which frequently inhabit microhabitats beneath small stones or within sediment interstices, are particularly vulnerable to mortality due to the physical disturbances caused by weighted trawl gear (Sea Spiders - Facts, Size, Habitat, Diet, Types, & Pictures). The most pronounced impacts of such fishing practices are observed on shallow and mid-depth continental shelves, where numerous species aggregate in proximity to prey fields, including hydroid beds and sponge communities that serve as essential food sources. Additionally, coastal pollution phenomena, such as eutrophication and the accumulation of heavy metals, further exacerbate the decline of these organisms by degrading intertidal and shallow-water ecosystems.

a. Climate change

Anthropogenic climate change represents one of the most significant threats to global biodiversity (Wudu, Abegaz, Ayele, & Ybabe, 2023). Extreme temperature events, which are increasingly associated with longer-term climate shifts, are manifesting with greater frequency, duration, and intensity. While the impacts of climatic extremes on ectothermic organisms, particularly insects, have been extensively documented in recent literature, the effects of extreme temperatures on other arthropod taxa, such as sea spiders (Pycnogonida), have been comparatively underexplored. Sea spiders play a crucial ecological role as predators within their respective ecosystems, underscoring the need for further research into their responses to climate stressors.

Table 1. Climatic change stressors on sea spiders.

Stressors	Effect on Sea Spider	Key risk
Ocean acidification	Impairs oxygen transport, higher mortality.	Causes physiological failure.
Ocean warming	Increases metabolic rate, causes oxygen stress.	Energy deficit and hypoxia.
Habitat loss	Disrupt the polar food web they depend on.	Loss of prey and specialized habitat.

b. Pollution

Environmental pollution, an escalating global concern, is impacting biodiversity and ecosystem stability across multiple levels (Seema Virbhan Keswani, 2025). Sea spiders, as integral predators within diverse ecosystems, exhibit a heightened vulnerability to environmental changes.

Table 2. Environmental pollution impact on sea spiders

Pollutants	Source	Effect on Sea Spider
Chemicals	Industrial and agricultural runoffs, oil spills.	Direct toxicity, mortality, impaired reproduction, and bioaccumulation.
Plastics and microplastics	Discarded single-use plastics, fishing gear, and microbeads.	Entanglement, ingestion, and habitat degradation.
Nutrient (Eutrophication)	Fertilizers and sewage runoffs	Creates low-oxygen “dead zones,” smothers habitats.
Noise	Shipping, construction, and sonar.	Potential disruptive behavior, stress.

c. Overfishing

Overfishing is defined as the extraction of specific fish species from aquatic ecosystems at a rate that exceeds their capacity for population replenishment, resulting in diminished populations of these species within the affected area (S. Sharma, Hampton, & Kimirei, 2024). In comparison to climate change, air pollution, or water pollution, the issue of overfishing is frequently marginalized in discussions of environmental degradation. Despite its implications as a precursor to the depletion of more marine resources, human activities continue to drive overfishing practices motivated by the pursuit of economic gain, which exacerbates and perpetuates avarice towards oceanic resources (Du, Sun, & Zhang, 2021). Moreover, overfishing compromises the resilience of fish stocks and aquatic ecosystems in the face of climate change (Sumaila & Tai, 2020); (Pauly, Watson, & Alder, 2005). This detrimental practice is further exacerbated by the use of destructive fishing techniques such as bottom trawling, which not only devastates the ocean floor but also adversely affects both targeted and non-targeted species (Wang, Leung, Sung, Dudgeon, & Qiu, 2021); (Jennings, Dinmore, Duplisea, Randall, & Lancaster, 2002). Overfishing exerts significant ecological consequences on marine ecosystems, primarily through the depletion of fish stocks and the alteration of marine biodiversity. One of the most immediate impacts of overfishing is the reduction in populations of targeted species, particularly large predatory fish that occupy upper trophic levels within food webs (Myers & Worm, 2003). The removal of these apex predators disrupts the natural equilibrium of marine ecosystems, precipitating trophic cascades in which the depletion of a single species induces a series of consequential shifts throughout the food web (Pauly et al., 2005). For instance, the overfishing of sharks has been associated with an increase in the populations of smaller mesopredators, which subsequently influences the abundance and diversity of prey species (Myers & Worm, 2003).

Table 3. Effect of overfishing on sea spiders

Impact mechanisms	Description	Effect on Sea Spider
Habitat destruction	Bottom trawling bulldozes complex seafloor structures (sponges, corals).	Loss of hunting ground and shelter
Trophic cascades	Removing key fish species alters the entire food web dynamics.	Unpredictable changes in food availability (either increased competition or prey collapse)
Bycatch	Accidental capture in fishing gear.	Direct mortality

Conservation efforts

a. Protected areas

Protected areas (PAs) serve as fundamental components of conservation strategies aimed at alleviating anthropogenic pressures that contribute to biodiversity loss (Li et al., 2024). Habitat loss, degradation, and fragmentation resulting from human activities are the critical factors driving an unprecedented decline in biodiversity (Powers & Jetz, 2019); (Sala et al., 2000); (Cardinale et al., 2012). The establishment and expansion of protected areas (PAs) have emerged as essential instruments employed by nations to mitigate and potentially reverse biodiversity loss, as these areas constitute the backbone of global conservation initiatives (Pringle, 2017); (Geldmann, Manica, Burgess, Coad, & Balmford, 2019). Researchers and policymakers are actively engaged in efforts to conserve marine biodiversity and ecosystem services through the establishment and management of marine protected areas (MPAs) (Rodríguez-Rodríguez & Martínez-Vega, 2022). Marine protected areas (MPAs) represent a primary global mechanism for halting the widespread decline of biodiversity in marine environments (Edgar et al., 2014). These designated marine zones act as sanctuaries that mitigate the impacts of human activities, including industrial fishing, pollution, and habitat degradation, all of which pose significant threats to the fragile ecosystems inhabited by sea spiders. By regulating fishing practices and restricting destructive activities, these protected areas facilitate the unrestricted movement and proliferation of sea spider populations, which play a vital role as scavengers in nutrient cycling and the maintenance of benthic community structures. Furthermore, protected areas contribute to the preservation of food webs, within which sea spiders are integral, thus supporting the overall health of marine habitats.

b. Research initiatives

Conservation initiatives directed at Pantopoda (sea spiders) have increasingly leveraged comprehensive research endeavors to elucidate the ecological roles of these enigmatic organisms within marine ecosystems. Such initiatives encompass a diverse array of strategies aimed at advancing both the biological investigation of sea spiders and the educational outreach essential for fostering public awareness and advocacy for conservation. Researchers are undertaking rigorous ecological studies to investigate the feeding behaviors, reproductive strategies, and habitat preferences of Pantopoda (Dietz et al., 2018). These investigations frequently involve field studies within marine environments, which are typically inhabited by a variety of benthic communities, to evaluate the interactions between sea spiders and other marine biota. A thorough understanding of these interactions is crucial for elucidating the role of sea spiders in nutrient cycling and the overall health of marine ecosystems. Research initiatives also prioritize the cataloging and identification of various sea spider species. Taxonomists are conducting assessments that evaluate biodiversity and identify species that are endangered or threatened due to environmental perturbations. Accurate taxonomic identification is imperative for effective conservation planning and for informing management strategies (Yunzhi Liu, Wang, Wu, Li, & Dai, 2024). A pivotal focus of contemporary research initiatives is the investigation of the impacts of climate change on sea spider populations and their associated habitats. Scholars are systematically analyzing variables such as temperature fluctuations, ocean

acidification, and habitat degradation, all of which pose significant threats to the intricate balance of marine ecosystems and jeopardize the viability of sea spider populations. To facilitate this inquiry, innovative tracking and monitoring programs are being implemented to elucidate the behavioral patterns and migratory movements of sea spiders. The data generated from these efforts is critical for evaluating population dynamics and reproductive success, as well as for comprehensively understanding the responses of these organisms to various environmental stressors. Interdisciplinary collaboration among researchers, conservation organizations, and governmental agencies is essential for the formulation of robust conservation strategies. Such partnerships ensure that empirical findings are effectively translated into actionable policies. Moreover, research outcomes have the potential to inform environmental policy, particularly concerning the safeguarding of marine habitats that are crucial to the survival of sea spiders. By actively engaging with policymakers, researchers endeavor to ensure that conservation strategies are informed by the most current scientific evidence, underscoring the imperative for habitat protection to preserve not only sea spiders but also the integrity of the entire marine ecosystem.

c. Public awareness and education

The imperative for enhanced conservation management of global marine ecosystems has reached a critical juncture (Easman, Abernethy, & Godley, 2018). Addressing significant global threats, including overfishing, pollution, habitat degradation, and climate change, is essential to preserve vital ecosystem services (Polidoro et al., 2008). Recent scholarly investigations indicate that adopting a more integrative approach to ecosystem management, coupled with heightened public engagement, may be a crucial determinant in the efficacy of marine conservation initiatives (Mapstone et al., 2008). Public awareness and education are integral to the conservation of sea spider populations. By disseminating knowledge to the public, stakeholders, and policymakers regarding the ecological significance of these distinctive marine organisms, advocates can cultivate support for conservation efforts and promote sustainable practices. This multifaceted educational outreach is vital for fostering a collective commitment to the protection of marine biodiversity and the resilience of marine ecosystems. These initiatives typically encompass workshops, seminars, and presentations that elucidate the ecological roles of sea spiders, their habitats, and the multifaceted challenges they confront. The development of educational materials such as brochures, fact sheets, and online resources that convey pertinent information about sea spiders is essential. These materials can be disseminated in educational institutions, aquariums, marine parks, and conservation centers, thereby facilitating the distribution of knowledge regarding their biology, behavior, and the critical importance of their conservation. The incorporation of marine biology, particularly the study of sea spiders, into school curricula has the potential to ignite student interest in marine conservation. Educational institutions may host programs, such as science fairs or field excursions to marine environments, thereby fostering a robust foundational understanding of marine ecosystems and the diverse species that inhabit them. Moreover, engaging the public in citizen science initiatives can enhance awareness of sea spiders while simultaneously contributing to valuable research endeavors. Volunteers can participate in monitoring programs, habitat restoration activities, and data collection regarding local sea spider populations. Educating the public on conservation issues is likely to cultivate grassroots advocacy for policies aimed at safeguarding marine ecosystems. Informed citizens can emerge as advocates for legislative measures that address threats to marine life, including habitat destruction and the impacts of climate change on sea spider populations.

Conclusion

Sea spiders, despite their frequently overlooked status, constitute integral components of diverse marine ecosystems. Their predatory behaviors serve to regulate invertebrate populations, thereby contributing to overall biodiversity and ecosystem stability. Furthermore, their involvement in nutrient cycling, especially the distinctive methane-consuming symbiosis observed in certain species, underscores their significant influence on biogeochemical processes. However, these essential organisms are confronted with substantial threats. Climate change, pollution, and overfishing, particularly through destructive practices such as

bottom trawling, are exerting severe pressures on sea spider populations. Additionally, phenomena such as ocean acidification, elevated water temperatures, and habitat degradation directly impact their physiological processes and survival prospects. Pollution from various anthropogenic sources introduces toxins and degrades the habitats of sea spiders. Overfishing practices employed by fisheries disrupt food webs, resulting in significant bycatch. Consequently, it is imperative for conservationists, researchers, and policymakers to act with urgency to formulate and enforce effective conservation strategies. The establishment and expansion of marine protected areas are critical for the preservation of sea spider habitats. Ongoing research initiatives that focus on species identification, ecological roles, and the impacts of climate change are essential for informing conservation efforts. Moreover, enhancing public awareness and promoting educational initiatives are vital for fostering support for sustainable practices and ensuring the long-term viability of these often-overlooked organisms. Only through a concerted effort that integrates scientific understanding, policy implementation, and public engagement can we secure the future of sea spiders and the health of the marine ecosystems they inhabit.

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Code and Data Availability

Data supporting the findings of this study are available within the article.

Author contribution

Michel Murwanashyaka: Writing an original draft, writing a review & editing.

Lihua Jiang: Supervision, writing a review & editing.

Xiaojun Yan: Supervision, funding.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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