Journal of Aquatic Biology & Fisheries | 2023 | 11(1) | pp. 28-34
ISSN 2321–340X
OPEN ACCESS
http://www.jabf.in/
University of Kerala, INDIA

Invasion of alien mussel *Mytella strigata* (Bivalvia: Mytilidae) in the Gulf of Mannar, India and possible threats to the native biodiversity

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ABSTRACT

The Gulf of Mannar between India and Sri Lanka is a biodiversity hotspot renowned for its coral reefs, seagrass beds, and mangrove ecosystems. This region, especially the Gulf of Mannar Marine Biosphere Reserve (GOMMBR), supports a diverse array of marine species, many of which are of ecological and economic importance, and this paper records the presence of invasive alien Charru mussel *Mytella strigata* along the mangrove and estuarine regions of the Gulf of Mannar, Tamil Nadu, India. The invasion of this mussel affects the native gastropod and bivalve species in the GOMMBR and the adjacent zones. This situation warrants urgent strategies and action plans to control their population in the GOMMBR and potential policies to manage the invasive species on the Indian coast, besides a detailed investigation of their invasion biology. Thorough scientific studies on the invasion biology of *M. strigata* could help understand the behaviour of the alien species, its ecological impacts, and potential control methods, besides better realising its economic implications. By integrating rainfall-related factors into management strategies, conservationists and policymakers can work towards mitigating the adverse effects of invasive mussels and preserving the health of aquatic ecosystems.

ARTICLE HISTORY

Received on: 30-07-2022
Revised on: 11-06-2023
Accepted on: 30-06-2023

KEYWORDS

Charru mussel,
Biosphere Reserve,
Mytella strigata,
Marine Invasion,
Invasion biology,
Gulf of Mannar

1. Introduction

Human-induced intentional or unintentional translocations of species outside of their natural range have been accelerated and facilitated through the process of globalisation (Seebens et al., 2021; IPBES, 2023), and biological invasions are now global concerns and one of the primary driving forces for biological extinctions (Bellard et al., 2016). Only foreign species that can establish themselves and spread are deemed invasive (Blackburn et al., 2011), and aquatic invasions may impact ecosystem services (Pejchar and Mooney, 2009), displacement of indigenous species (Grosholz, 2002; Perrings, 2002; Wallentinus and Nyberg, 2007; Molnar et al., 2008; Troost, 2010; Vilà et al., 2010), and predation of local species (Katsanevakis et al., (2014). Information on marine bioinvasion and their pathways are still limited compared to terrestrial or freshwater ecosystems, and therefore, understanding the causes and effects of marine invasion processes and their implication on ecosystems, their vectors, and routes of introduction is essential in developing effective control and management strategies (Biju Kumar and Ravinesh 2017; Ros *et al.*, 2023).

Ballast water and fouling are the major sources of invasive species introductions in marine ecosystems globally Padilla and Williams (2004); Steven (2021), and molluscs, particularly mussels, are one of the major marine taxa that have established successfully in non-native environments, primarily because of their evolutionary resilience and long evolutionary history (Lim *et al.*, 2018). The mytilid mussel *Mytella strigata*, a native of South America (Boehs *et al.*, 2004; Darrigrán and Lagreca, 2005; Boudreaux and Walters, 2006), has been reported recently from different Asian countries such as the Philippines (Rice *et al.*, 2016; Mediodia *et al.*, 2017; Vallejo *et al.*, 2017 and Fuertes *et al.*, 2021), Singapore (Lim et al., 2018; Yip et al., 2021), Thailand (Sanpanich and Wells, 2019), Caribbean (César et al., 2021), Taiwan (Huang et al., 2021) and India (Biju Kumar *et al.*, 2019 and Jayachandran et al., 2019). In India, the invasive alien mussel *M. strigata* spreads extensively in most estuarine and brackish water ecosystems of Kerala (Biju Kumar et al., 2019; Jayachandran et al., 2019). This species impacts the native Asian green mussel *Perna viridis* fishery in India (Biju Kumar et al., 2019) and Thailand (Sanpanich and Wells, 2019). Biju Kumar et al. (2019) also recorded the gradual decline in the population of backwater oysters such as *Magallana bilineata*, *Saccostrea cucullata* and native clams *Marcia recens* and *Villorita cyprinoides* due to the invasion of *M. strigata* in Ashtamudi estuary, southwest coast of India.

The Gulf of Mannar Marine Biosphere Reserve (GOMMBR) lies between India and Sri Lanka. It encompasses the territorial waters of the southeast coast of India, from Dhanushkodi in the north to Kanyakumari in the south. GOMMBR consists of several ecosystems, such as coral reefs, rocky shores, sandy beaches, mudflats, seaweeds, seagrasses, and mangroves, supporting characteristic biocoenosis (Kumaraguru *et al.,* 2006; Ramesh et *al.,* 2020 and Edward *et al.*, 2022). These ecosystems support a wide variety of marine biodiversity in this region. The molluscan diversity of the Gulf of Mannar is very high; more than 1466 species were recorded from this locality (Edward *et al.*, 2022).

This study records the invasion of *M. strigata* in the GOMMBR and forwards comments on its possible impacts on the mangrove and brackish water molluscan communities.

2. Materials and Methods

The *Mytella strigata* populations were initially documented at GOMMBR in August 2020. Subsequent periodic molluscan surveys conducted at the GOMMBR region from June 2020 to June 2022, recorded the invasive *Mytella strigata* populations in the estuarine, brackish water and mangrove regions, Punnakayal, Mottaigopuram and Inigo Nagar of Tuticorin, Tamil Nadu, southern east coast of India. They were found buried in muddy-sand sediments and attached to protective walls, floating artificial structures, rocky substrates, bridges and mangrove regions of the Gulf of Mannar, Tamil Nadu (Fig. 1). Sample collections were done during low tide; the mussel diversity was studied using randomly placed 1m x 1m PVC quadrates. All the *M. strigata* and associated molluscs were collected by handpicking and digging. The collected specimens were identified with appropriate research literature (Huber, 2010; Coan and Scott, 2012; Biju Kumar *et al.*, 2019; Scott *et al.*, 2020 and Edward *et al.*, 2022).

3. Results and Discussion

Invasive species can alter the physical and ecological characteristics of habitats (Middleton 2018). They may modify soil chemistry, disrupt natural water flow, or change the structure of ecosystems, making them less suitable for native species (Pyšek and Richardson, 2010; Middleton, 2018; Mayfield et al., 2021). The populations of *Mytella strigata* were recorded from different habitats of the Gulf of Mannar Biosphere Reserve, southeast coast of India (Fig. 2A-F). This study documented the average population of 1069m^2 (Fig. 3). The average population density in various regions is as follows: muddy, sandy regions along the shoreline (1151m^2); floating cages, pillars, bridges and artificial structures (2012m^2); mangroves and associated environments (46m^2).

The population density was maximum (2040m^2) during the premonsoon (April 2021 to August 2021 and April 2022 to July 2022) and less during the monsoon and post-monsoon (September 2021 to March 2022)(390m^2). Because these mussels are filter feeders and rely on plankton as a food source, reduced rainfall and drought can lower water levels and decrease plankton availability, potentially affecting the invasive mussel population's survival and reproduction. Rainfall can affect water quality, which may indirectly influence the competitive advantage of invasive mussels. Sudden heavy rains can cause temperature fluctuations, particularly in smaller water bodies. These fluctuations can stress invasive mussels; low salinity and temperature stress can affect their metabolic rates and overall fitness, potentially impacting the competitive ability of the *M. strigata*. They can also survive large fluctuations in salinity for long and short periods; *M. strigata* tolerates a wide range of salinities as low as 2 ppt and as high as 40 ppt (Yuan et al., 2010; Rice et al., 2016).

In one of the extensive studies on the molluscan diversity of the Ashtamudi estuary, Ravinesh et al. (2021) did not record *Mytella strigata* from the region from February 2017 to January 2018. Therefore, it may be assumed that the rapid spread of *M. strigata* was started after the very severe cyclonic storm Ockhi (November 2017). After the cyclone, from March 2018 onwards, Biju Kumar et al. (2019) recorded *M. strigata* from the Neendakara Barmouth, Ashtamudi estuary, southwest coast of India. Simultaneously, Jayachandran et al. (2019) recorded *M. strigata* from the Cochin backwaters from May 2019 onwards. There are no other records of *M. strigata* from the mainland coast of India and oceanic islands. In the present study, we report the expansion of the range of *M. strigata* in the Gulf of Mannar on the east coast of India, and it has

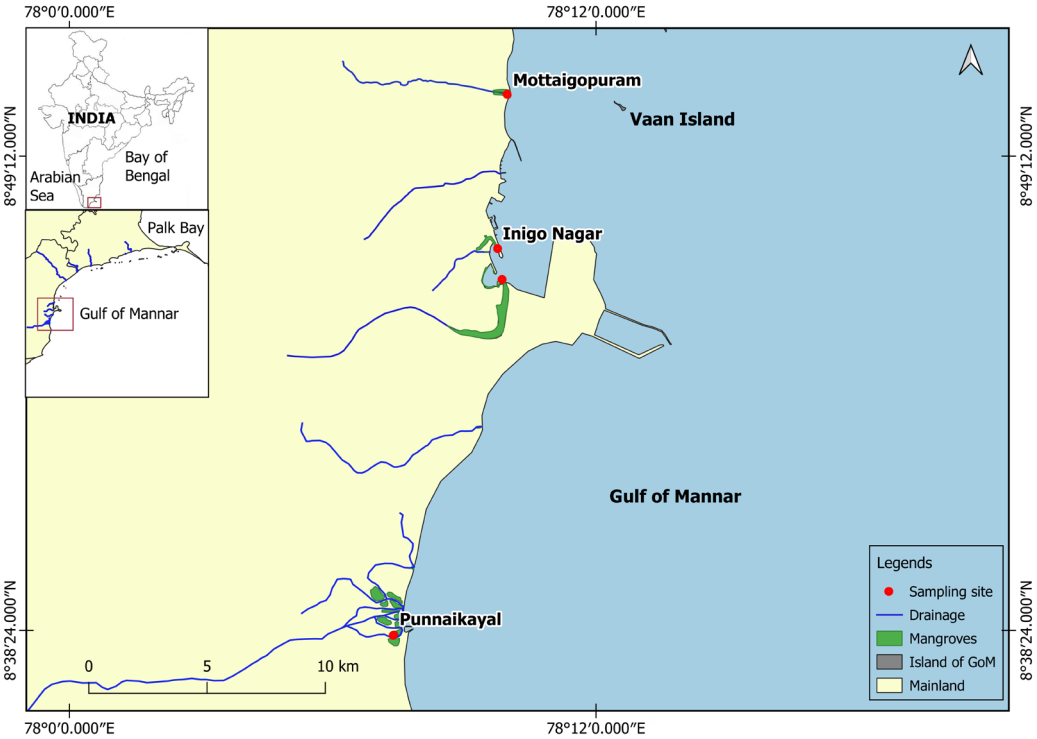

Fig. 1. Map showing the areas of occurrence of *Mytella strigata* in the Tuticorin coast of the Gulf of Mannar

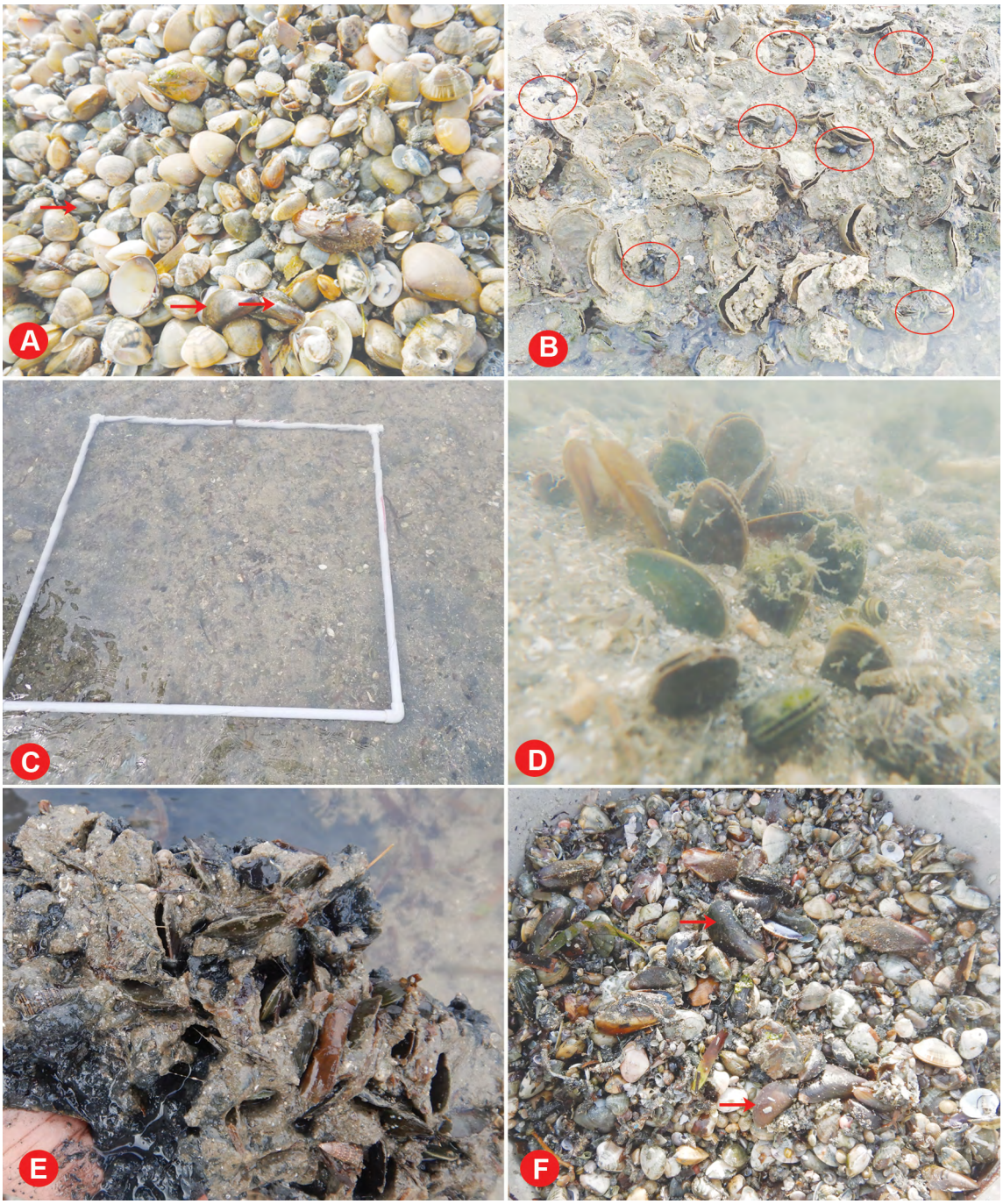

Fig. 2A. Venerid clams and associated with invasive Charru mussel *Mytella strigata* (red colour arrow mark); **B.** Invasion started from the *Magallana bilineata* bed (red colour circle); **C.** 1x1m^2 quadrat muddy region; **D.** Underwater photo *M. strigata* on beds of ornamental gastropod *Clithon oualaniense;* **E.** Mussel collected from muddy bottom; **F.** Venerid clams and ornamental gastropods associated with invasive Charru mussel *Mytella strigata* (red colour arrow mark).

also been observed in other estuarine regions along the east coast of India.

Bivalve production from Tamil Nadu and Pondicherry was estimated at 1,441 tonnes; clams contributed 50.6%, followed by mussels (26.1%) and oysters (23.3%) (CMFRI 2019). The native molluscs have been recorded in the locality through the ongoing survey of the researchers (Table 1).

The list of co-occurring native molluscs in GOMMBR, along with alien *M. strigata,* are listed in Table 1. As the exotic mussels may develop massive populations quickly in major biomes in GOMMBR, such as sandy, muddy, mangroves, artificial structures, bar mouth and brackish water, their impact on native species may be studied in detail to realise the biodiversity and ecosystem impacts. *Mytella strigata* is an active filter feeder that forces water through its gills to remove particles. All the invasive mussels can consume organic matter, bacterial colonies, phytoplankton and detritus. *M. strigata* competes with native filter-feeding bivalves such as clams, oysters and other natives.

Mytella strigata is a marine invasive species (MIS) that established considerable populations outside its natural range (Boudreaux and Walters, 2006; Gillis *et al*., 2009; Rice *et al*., 2016; Mediodia *et al*., 2017; Vallejo *et al*.,

Table 1. List of native species of molluscs co-occurring with the alien *Mytella strigata* in GOMMBR.

No	List of Species	Uses
	Family: Trochidae	
1.	*Umbonium vestiarium* (Linnaeus, 1758)	Ornamental and Food
	Family: Neritidae	
2.	*Clithon oualaniense* (Lesson, 1831)	Ornamental
3.	*Neripteron violaceum*(Gmelin, 1791)	Ornamental
	Family: Potamididae	
4.	*Pirenella cingulata* (Gmelin, 1791)	Ornamental and Lime Industry
5.	*Telescopium telescopium* (Linnaeus, 1758)	Ornamental
	Family: Nassaridae	
6.	*Nassarius jacksonianus* (Quoy and Gaimard, 1833)	Ornamental
7.	*Nassarius pullus* (Linnaeus, 1758)	Ornamental
	Family: Mytilidae	
8.	*Modiolus modulaides* (Röding, 1798)	Ornamental, Food and Lime Industry
9.	*Modiolus philippinarum* (Hanley, 1843)	Lime Industry
	Family: Ostreidae	
10.	*Magallana bilineata* (Röding, 1798)	Food and Lime Industry
11.	*Saccostrea cucullata* (Born, 1778)	Food and Lime Industry
	Family: Mesodesmatidae	
12.	*Atactodea striata* (Gmelin, 1791)	Ornamental, Food and Lime Industry
	Family: Tellinidae	Lime Industry
13.	*Jitlada philippinarum* (Hanley, 1844)	
14.	*Quadrans gargadia* (Linnaeus, 1758)	Lime Industry
15.	*Gastrana multangula*(Gmelin, 1791)	Lime Industry
	Family: Psammobiidae	
16.	*Gari maculosa* (Lamarck, 1818)	Lime Industry
17.	*Gari squamosa* (Lamarck, 1818)	Lime Industry
	Family: Veneridae	
18.	*Dosinia cretacea* (Reeve, 1850)	Ornamental, Food and Lime Industry
19.	*Dosinia histrio* (Gmelin, 1791)	Ornamental, Food and Lime Industry
20.	*Gafrarium pectinatum* (Linnaeus, 1758)	Ornamental, Food and Lime Industry
21.	*Gafrarium tumidum* Röding, 1798	Ornamental, Food and Lime Industry
22.	*Marcia opima* (Gmelin, 1791)	Ornamental, Food and Lime Industry
23.	*Marcia recens* (Holten, 1802)	Ornamental, Food and Lime Industry
24.	*Meretrix aurora* Hornell, 1917	Ornamental, Food and Lime Industry
25.	*Meretrix casta* (Gmelin, 1791)	Ornamental, Food and Lime Industry
26.	*Pelecyora ceylonica* (Dunker, 1865)	Food and Lime Industry
27.	*Ruditapes bruguieri* (Hanley, 1845)	Food and Lime Industry
	Family: Solenidae	
28.	*Solen vaginoides* Lamarck, 1818	Food and Lime Industry
	Family: Laternulidae	
29.	*Laternula anatina* (Linnaeus, 1758)	Lime Industry

2017; Lim *et al*., 2018; Spanish and Wells, 2019, Biju Kumar *et al*., 2019; Jayachandran *et al*., 2019). In Kerala, Biju Kumar et al. (2019) recorded a higher population of *M. strigata,* up to 6240 individuals m^2 along the shoreline, and 10152 individuals m^2 in floating cages, pillars, bridges and artificial structures; they have documented the gradual decline in the population of backwater oysters such as *Magallana bilineata and Saccostrea cucullata,* short neck clam *Marcia recens,* black clam *Villorita cyprinoides* Asian green mussel *Perna viridis* and other *mytilids* such as *Arcuatula* sp*., Brachidontes pharaonis, Brachidontes* sp. and *Modiolus modulaides* from the Kerala, southwest coast of India.

Introducing *Mytella strigata* to non-native areas can negatively impact local ecosystems and reduce biodiversity by displacing or competing with native species. This species can outcompete native species for resources, alter habitat structures, and disrupt local food chains. They often thrive in new environments without natural predators or competitors. Efforts to manage or control invasive species like *Mytella strigata* typically involve a combination of measures such as monitoring, containment, and eradication when feasible. Further research, including experimental introductions, case studies, and modelling, is crucial to understanding the behaviour and impact of invasive species in new environments. This information can help inform management strategies. Few other areas of research focus in India could be: (i) Analyse the factors contributing to the rapid dispersal and establishment of *M. strigata* populations in new environments; (ii) Explore genetic diversity and the potential for adaptive evolution in introduced populations; (iii) Assess the competitive advantage of *M. strigata* over native mussel species and its impact on native communities; (iv) Influences on ecosystem functions and services; (v) Physical alterations caused by *M. strigata* its consequences for native habitats; and (vi) Consider the influence of changing environmental conditions including climate change, on the distribution and impact of *M. strigata*.

Preventing the introduction of invasive species in the first place through measures such as ballast water management and stricter biosecurity regulations is a critical step in invasive species management (Giakoumi et al., 2019). Once invasive species become established, controlling or eradicating them can be challenging. Physical or mechanical removal may be labour-intensive and costly, especially for widespread populations. Chemical control should be used cautiously to avoid ecological impacts, often becoming unmanageable. Protocols for early detection, including the e-DNA approach, can be adopted to monitor *M. strigata* populations in vulnerable coastal areas. Promoting the use of invasive species as value-added products or for human consumption can help reduce

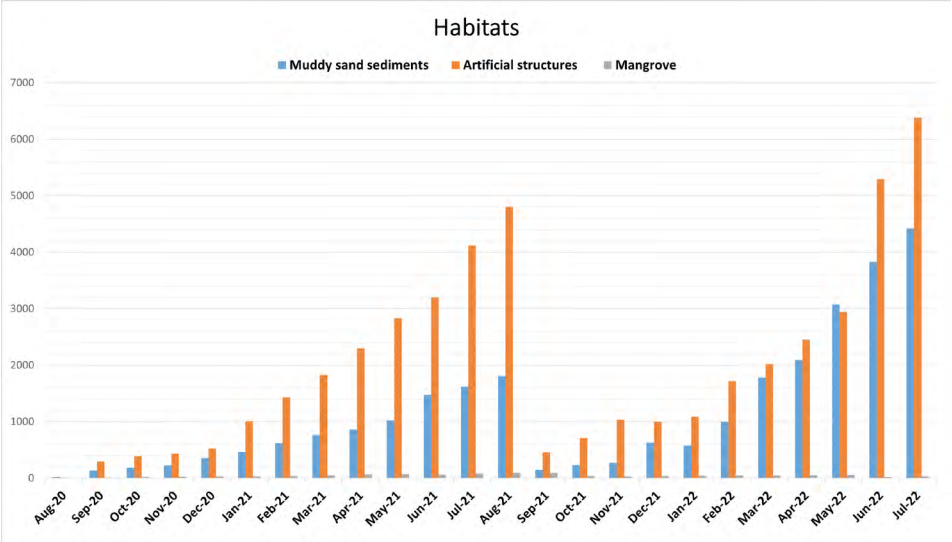

Fig. 3. Population of *Mytella strigata* from August 2020 to July 2021.

their populations and provide economic incentives for their management. Field observations reveal that the mussel is currently used as duck and fish feed in regions around Ashtamudi Lake, Kerala. Promoting human consumption and manual removal may be a control method to reduce or manage population size. That is one of the controlling measures to address the rapid invasion. Presently, no assessment of the economic impacts of *M. strigata* has has been undertaken in India. This study recommends that the invasion of *M. strigata* and the possibility of threatening other estuarine molluscan communities in the future also need more exploratory surveys requiring large and minor estuaries all along the Indian coasts and collaborate with international organisations and neighbouring countries to address the issue of invasive species, especially through the legally binding ballast water management regimes.

Managing the invasion of alien mussel *Mytella strigata* in coastal ecosystems is a multifaceted challenge that requires a coordinated and science-based approach, first in understanding invasion biology and second, in appropriate region-based management strategies with stakeholder involvement, especially with the participation of fishing communities. Rainfall patterns can also influence management strategies for controlling invasive mussels. Annual rainfall can significantly impact the distribution, spread, and survival of invasive mussels in aquatic ecosystems. Understanding the relationship between rainfall and invasive mussels is vital for managing and mitigating the negative impacts of these invasive species on native ecosystems. Researchers or policy makers can use data on rainfall and invasive mussel distribution to develop predictive models that help anticipate where invasive mussels are likely to establish and spread. These models can inform proactive management and prevention efforts. By integrating rainfall-related factors into management strategies, conservationists and policymakers can work towards mitigating the adverse effects of invasive mussels and preserving the health of aquatic ecosystems. This study suggests that in order to execute efficient management strategies and design management programmes, the invasion of *M. strigata* and its effects on native molluscan communities and ecosystem services, as well as the economic repercussions of invasion, need to be studied in detail.

Acknowledgements

We thank the SDMRI technical staff, Sahaya Mani and Stephan Raj, for their field work support. Thanks also to Dr. N. Gladwin Gnana Asir, SDMRI, for preparing the location map. The authors from the University of Kerala also thank the international research project ECOMARINE (Building a Comprehensive Mechanism for Preserving Marine Ecosystems and Life from the Negative Consequences of Climate Change and the Disposal of Plastic Debris) supported under the Erasmus + scheme of the European Union for the support.

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