ISSN 2321–340X

Journal of Aquatic Biology & Fisheries | Vol. 7 | 2019 | pp. 31 - 45

RAPID BIOINVASION OF ALIEN MUSSEL *MYTELLA STRIGATA* (HANLEY, 1843) (BIVALVIA: MYTILIDAE) ALONG KERALA COAST, INDIA: WILL THIS IMPACT THE LIVELIHOOD OF FISHERS IN ASHTAMUDI LAKE?

Biju Kumar, A.,[1] Ravinesh, R.,[1*] Oliver, P.G.,[2] Tan, S.K.[3] and Sadasivan, K.[4]

[1]*Department of Aquatic Biology and Fisheries, University of Kerala, Thiruvananthapuram- 695581, Kerala, India*
[2]*National Museum of Wales, Cathays Park, Cardiff, CF10 3NP, UK*
[3]*Lee Kong Chian Natural History Museum, National University of Singapore, Singapore*
[4]*Travancore Nature History Society (TNHS), Vanchiyoor, Thiruvananthapuram, Kerala, India*
**Email: ravineshr08@gmail.com*

Abstract: Bioinvasion is a growing concern in aquatic ecosystems as it severely impacts biodiversity, causing ecosystem changes and heavy economic losses. The invasive bivalve mussel *Mytella strigata* (Hanley, 1843) is spreading in many estuarine ecosystems and brackishwater lakes in Kerala coast. Its rapid spread across the state might have been triggered by Ockhi, a strong tropical cylone in the Arabian sea that struck the Kerala coast in 2017. Furthermore, the frequent transport of fishing vessles from the inshore waters to the estuaries must have facilitated their spread. This study reveals that the rapidly increasing biomass of *M. strigata* in Ashtamudi Lake, a Ramsar site in Kerala, has wiped out the populations of green mussel (*Perna viridis*) and their massive settlement in many areas has replaced the dominant clam species (short-neck clam or yellow-foot clam, *Marcia recens*) and backwater oysters *Magallana bilineata* and *Saccostrea cuccullata* populations, which support the livelihoods of hundreds of fishers in the area, besides damaging the aquaculture systems. The increasing populations of *M. strigata*, coupled with its ability to survive across the salinity gradients from the mouth of the estuary to the river discharge zone in the tail end, may have long-term implications on biodiversity and ecosystem services of the lake.

Key words: Estuary, Alien species, Oyster, Mussel, Salinity tolerance, Invasion biology

INTRODUCTION

Bioinvasion or the establishment of non-native species / non-indigenous species/ alien species outside its native range, has been relatively well documented in freshwater and terrestrial environments, though of late, there are increasing numbers of records from marine and estuarine ecosystems. This has been linked especially with the escalation of maritime transportation, trade of living organisms, climate change and coastal developmental activities including development of maritime canals (Carlton, 1996; Winder *et al.*, 2011; Galil *et al.*, 2014; Ojaveer *et al.*, 2018). The impacts recorded in marine habitats due to the invasion of non-native species include displacement of native species, changes in community structure and trophic interactions, fouling of ship's hulls, clogging of pipes, nutrient cycling, sedimentation as well as impacts on human health (Molnar *et al.*, 2008; Occhipinti-Ambrogi and Galil, 2010). Though bioinvasion has been identified as a major threat to marine biodiversity, there are several limitations in developing appropriate management strategies due to the lack of baseline historic data on biodiversity and invasions, besides the lesser amount of research in this field (Ojaveer *et al.*, 2018).

The bivalve family Mytilidae, commonly known as mussels, has two main modes of living although both depend on byssal attachment. Many are truly epifaunal, living attached to hard substrates such as rocky shores but also on man-made structures including seawalls and cages, and sedimentary coasts, in both marine and estuarine environments (Scarabino *et al.*, 1975; Coan and Scott, 2012). This group is typified by the economically important genera *Mytilus* and *Perna*. The second life habit is semi-endobyssate where the mussel lives partially buried in soft sediments ranging from muds to gravels. This group is typified by the genus *Modiolus* but many others can colonise soft sediments especially if there are any hard object to facilliate attachment. When this happens even epibyssate taxa can colonise soft substrates. The epibyssate genera form an economically valuable fishery resource and aquaculture resource in many regions of the world (Suchanek, 1986; Buschbaum *et al.*, 2009). With their excellent dispersal and colonisation capacity in different environments, mussels have become successfully established in several regions across the world (Gillis *et al.*, 2009). The most wide spread of these has been *Musculista senhousei* (Benson, 1842), originally from East Asia but now through out the Indo-Pacific, Mediterranean, NE Atlantic, Caribbean and East Pacific (GISD, 2019).

Recently the American brackish water mussel *Mytella strigata* (Hanley, 1843) [known in literature also as *M. charruana* (d'Orbigny, 1842), actually published in 1846; see Lim *et al.*, 2018] has been found well beyond its native range. It is native to Atlantic coast of South America and the Pacific coast of Central and South America from Mexico to Ecuador (Boehs *et al.*, 2004; Darrigrán and Lagreca, 2005; Boudreaux and Walters, 2006). Outside its natural range, this species has been recorded from Florida and Georgia (Boudreaux and Walters 2006; Gillis *et al.*, 2009), Philippines (Rice *et al.*, 2016; Mediodia *et al.*, 2017; Vallejo *et al.*, 2017a,b), Singapore (Lim *et al.*, 2018) and Gulf of Thailand (Sanpanich and Wells, 2019). Recently presence of *M. strigata* was reported from the Vembanad Lake of Kerala, India by Jayachandran *et al.* (2019).

This paper documents the presence of *M. strigata* from various estuaries and backwater systems of Kerala, and explores its possible impacts on the livelihoods of fishers of Ashtamudi Lake, along with its ecosystem implications.

MATERIALS AND METHODS

Specimens of the invasive mussel *M. strigata* were collected from rocky substrates, floating artificial structures, protective walls, bridges, pillars, and from bottom sediments of estuaries and brackish water lakes of Kerala state, India, as part of the ongoing marine biodiversity survey along Kerala coast of India. For determining the density, 1 x 1 m PVC quadrates were placed on the mussel colonies and every specimen within each quadrate was collected by scraping the entire biomass on the substratum using a knife or chisel. The collected mussels were transferred to boats and counted. Representive samples of 25 individuals were measured using digital calipers to record the length and width of the shells. Collections were made by skin diving and with the help of local fishers. The collected specimens were identified using Huber (2010) and Coan and Scott (2012).

Seasonal surveys were conducted in Ashtamudi Lake ($8^0$45' - $9^0$28' N; $76^0$28' - $77^0$17' E), a brackish water Ramsar Lake located in Kollam district of Kerala, southwest coast of India during 2017 to 2019. Considered as the gate way to the back waters of Kerala, this lake opens into the Arabian Sea and receives the freshwater flow from the Kallada River originating from the Western Ghats. The fishers involved in molluscan fisheries were interviewed to record the presence of *M. strigata* in various fishing grounds and to understand the implications of non-native species on their livelihoods, based on their perceptions.

RESULTS

Distribution range

The survey along the Kerala coast, southern west coast of India during 2017-2019 period recorded specimens of *Mytella strigata* from Kadinamkulam, Paravur, Edava- Nadayara, Ashtamudi, Kayamkulam, Vembanad, Chettuvai, and Ponnani estuaries/backwaters of Kerala (Fig. 1). The specimens of *M. strigata* were collected initially during March 2018 from the Neendakara barmouth

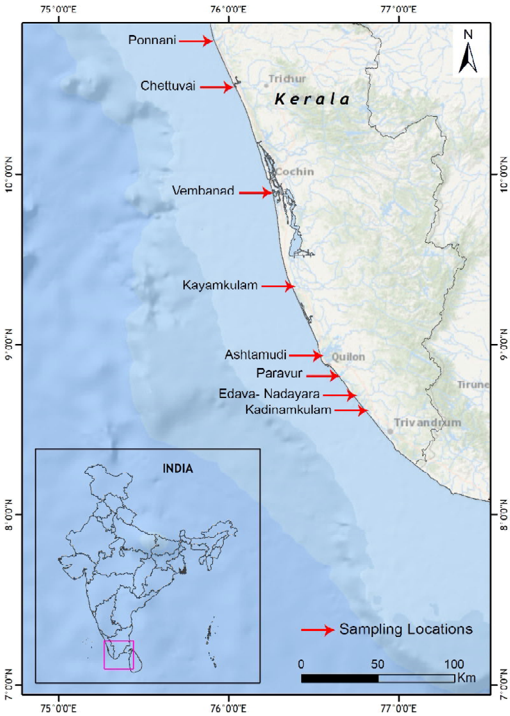

Fig. 1. Map of Kerala state, India showing the areas of occurrence of *Mytella strigata*

region of Asthtamudi estuary. Subsequent samplings recorded their presence in eight estuarine / backwater ecosystems from Kadinamkulam backwater in the south of Kerala to Ponnani estuary in the northern part of Kerala, indicating the spread of the species all along Kerala coast (Fig. 1).

Species Account

Superfamily: Mytiloidea Rafinesque, 1815

Family: Mytilidae Rafinesque, 1815

Subfamily: Arcuatulinae Scarlato & Starobogatov, 1979

Genus: *Mytella* Soot-Ryen, 1955

***Mytella strigata* (Hanley, 1843)** (Fig. 2 A-E and Fig. 3 A-X)

Mytella strigata can be easily identified by the presence of two small teeth on the anteroventral margin (Fig. 2 C), that appear as very short external ridges below the beaks. Shell length 15 mm to 63mm, modioliform, beaks subterminal less so in juveniles, venrtral margin incurved, posteriorly flared. Two small teeth present subumbonally, these corresponding to very short exterior riblets exteriorly. Anterior adductor scar small. Exterior sculpture of irregular low co-marginal ridges posteriorly and dorsally, anterior ventral area smooth or with very faint radial striations only visible when shell is dry. Periostracum colour varying black wavy dark (brown, purple, dark green) and light (cream) pattern, dark brown or green. Interior iridescent purple, olive green to greenish-purple.

The brown mussel *Perna perna* (Fig. 2. F-I) differs from *Mytella strigata* in reaching a much larger size, having terminal beaks and being of a general brown to greenish brown colour. The subumbonal region has no external riblets and there is but a single interior tooth in the right valve. There is no anterior adductor muscle in the genus *Perna*.

Green mussel *Perna viridis* (Fig. 2. J-M) is very similar to the brown mussel but is generally more brightly coloured green and possess the characteristic dysodont teeth, two on left valve and one on right valve.

Since they share the habitats along the Kerala coast the green mussel (*Perna viridis*) and brown mussel (*Perna perna*) are often mis-identified by the local fishermen.

Density

Though maximum density of mussels was recorded from areas high in salintity (35 to 20 ppt), they were collected from areas as low as 2 ppt in Ashtamudi Lake. Mussels were also collected from the mangrove marshes and benthic areas dominated by sand and clay. The maximum density of *Mytella* recorded from various estuaries and brackish water lakes of Kerala coast is as follows: Kadinamkulam Lake- 621 ind. ± 14 m^{-2}; Paravur Lake- 548 ind. ± 21 m^{-2}; Edava-Nadayara backwaters- 457 ind. ± 8 m^{-2}; Ashtamudi Lake- 11384 ind. ± 2131 m^{-2}; Kayamkulam Lake- 393 ind. ± 14 m^{-2}; Vembanad Lake- 1451 ind. ± 29 m^{-2}; Chettuvai and Ponnani– 212 ind. ± 17 m^{-2}. The results clearly indicate that maximum density of the invaded mussel occurs in Ashtamudi Lake of Kerala.

Size range

The range of length x width (mm) prepared based on 100 specimens randomly selected from the quadrates is as follows: Kadinamkulam Lake- 8.6 – 51.3 x 4.0 - 22.9 mm; Paravur Lake- 7.5 – 48.6 x 3.8 - 21.2 mm; Edava- Nadayara backwaters- 6.1 – 52.8

Fig. 2 A-E. Invasive Charru mussel *Mytella strigata*; **F-I.** Green mussel *Perna viridis;* **J-M** Brown mussel *Perna perna*

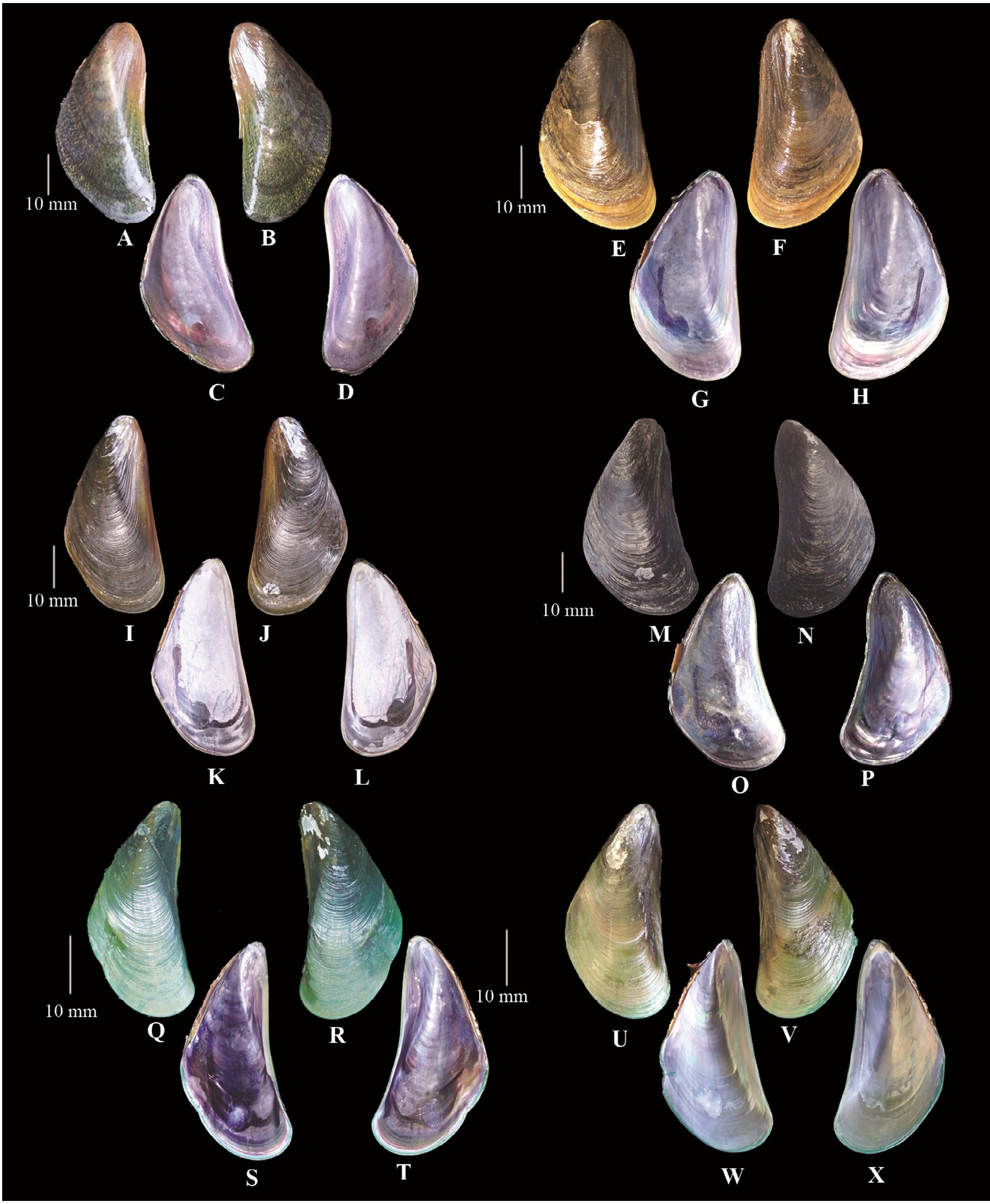

Fig. 3 A-X. Morphotypes of Charru mussel collected from the Kerala coast

x 3.6 - 23.7 mm; Ashtamudi Lake- 9.2– 63.1 x 4.0 - 24.9 mm; Kayamkulam Lake- 8.2 – 53.5 x 3.9 - 23.9 mm; Vembanad Lake 9.2– 62.3 x 4.0 - 25.2 mm; Chettuvai 7.3– 47.1 x 3.7 - 22.8 mm, and Ponnani – 5.1 – 42.4 x 2.9 – 19.7 mm.

Morphotypes (Fig. 3 A-X)

The shell morphology of specimens collected from various estuaries and backwaters of Kerala followed typical modioliform outline, characterised by nearly terminal or subterminal umbones. The shell colour patterns showed great variations and typically four general patterns were observed: (1) with brownish anterior part and greenish posterior part bearing cross marks at postero-lateral side; interior of shell light purple (Fig. A-D); (2) brownish yellow form with varying thickness of commarginal lirae; interior of shell silvery purple (Fig. E-P); (3) with brownish anterior and greenish yellow posterior; interior of shell dark purple (Fig. Q-T); (4) with brownish anterior and olive green posterior; interior of shell light purple. In all the cases, the animal's body is yellowish, with brown to black pigmentation along the mantle and foot. Byssus threads are fine and flattened.

Ecosystem and livelihood implications

Among the various estuaries and backwaters of Kerala, invasion of *M. strigata* is most intensive in the Ashtamudi Lake and the invasive mussel has established breeding populations in the last two years (2018 and 2019). Previous surveys conducted by the senior authors have not recorded these animals from this lake, which suggests their presence in far smaller numbers, if they were present at all. The fishermen engaged in molluscan fisheries in the region, especially those involved in clam fisheries, say that they have seen larger number of these 'Varathan Kakka' (which in local language Malayalam means alien bivalve mollusc) in the last few years, particularly after the strong tropical cylone Ockhi in the Arabian Sea that struck Kerala coast in 2017.

Along the coastal waters of Kollam district and in the mouth of the Ashtamudi Lake, where the the twin fishing harbours (Neendakara and Sakthikulangara) are located and the lake opens into the Arabian Sea, *M. strigata* have entirely covered the intertidal rocks and the rocky reefs below water (which are exposed during low tide; Fig. 4 A). Here they have largely replaced the green mussels (*Perna viridis*) that were once abundant in the area. The green mussel communities once recorded as abundant in the mouth of the estuary as late as 2017, are now found only in isolated patches along the estuarine mouth. The *M. strigata* populations have also fully encrusted the wharf and all concrete structures (Fig. 5 A) all along the harbour. As foulers, the invasive mussels are also been reported from the hulls of ships and fishing vessels (Fig. 5 B) in the area, coconut pillars of Chinese fishing nets (Fig. 4 B) and stake nets, and aquaculture systems.

As the invasive mussels settle in byssal nests on the lake bed, *M. strigata* now dominates the benthic biomass of the Ashtamudi estuary (Fig, 4 C, F), reaching a maximum of 11384 individuals per square meter. This may change the ecosystem services and biodiversity of the region considerably. In many areas near the mouth of Ashtamudi estuary, blankets of *M. strigata* now smother the beds of Ashtamudi short-neck clams (*Marcia recens*) (Fig. 4 E). More importantly Ashtamudi Lake supports the livelihood of hundreds of fishermen involved in clam fishing (Fig. 5 D), and abundance of *Mytella* has reduce the availability of clam resources. *Mytella* has settled heavily both in sandy and clayey bottoms of the lake, especially in the shallow water channels subjected to tidal flows (Fig. 4 C, F) and in the mangrove marshes (Fig. 4 E). Considering the fact that the presence of *Mytella* has been recorded only during this study from 2018 and that the certified Ashtamudi short-neck clam fisheries has been continuously monitored by researchers, the rapid spread of *M. strigata* population should be a matter of utmost concern, as in the long-term it could negatively impact the livelihood of fishermen in the area. Furthermore, fishermen in the Ashtamudi Lake are also employed in the collection of green mussel (*Perna viridis*), and backwater oysters *Magallana bilineata* and *Saccostrea cuccullata* (Fig. 4 A,B). Fisherfolks also opinioned that the less saline areas are used by them to harvest black clam *Villorita cyprinoides*, and the invasive mussel has become a threat there too. The increasing biomass of invasive mussel would severely impact the resource availability for the fishers in the long run.

Fig. 4 A. Invasive Charru mussel *Mytella strigata* on intertidal rocks in Ashtamudi barmouth once dominated by *Perna viridis* populations; **B.** Fouling on coconut pillar of Chinese fishing net; **C.** *Mytella strigata* collected from muddy bottom; **D.** Underwater photo *M. strigata* on beds of short-neck clam (arrow mark); **E.** *M. strigata* in muddy bottom; **F.** Mussel collected from mangrove marsh.

Fig. 5 A. *Mytella strigata* attached to granite walls; **B.** Fouling of mussels (arrow) in fishing boat; **C.** Invasive mussels settled on ropes of oyster culture; **D**. Clam fishing in Ashtamudi Lake.

Ashtamudi Lake has been used by many fishers to perform cage cuture of finfishes and rope culture of edible oyster *Magallana bilineata*. Heavy fouling with invasive mussel has been observed in aquaculture cages and settlements of larvae have also been observed on the ropes and shells used for the edible oyster culture (Fig. 5 C). This may bring economic losses to fishers in the locality and may hinder aquaculture operations.

DISCUSSION

Mytella strigata is a proven marine invasive species (MIS), that has established sizeable populations outside its natural range (Boudreaux and Walters, 2006; Gillis *et al.*, 2009; Rice *et al.*, 2016; Mediodia *et al.*, 2017; Vallejo *et al.*, 2017a,b: Lim *et al.*, 2018; Sanpanich and Wells, 2019), including in India, where it has been recorded from the brackishwater Vembanad Lake of Kerala (Jayachandran *et al.*, 2019). The origin of invasive *M. strigata* populations that invaded Asian countries has been conclusively proven based on molecular phylogeny to be from the Caribbean coast of South America (Rice *et al.*, 2016; Lim *et al.*, 2018).

The success of establishment and rapid invasion potential of mytilids all over the world is attributed to their high fecundity, fast growth rate, tolerance to wide range of environmental thresholds, a short lifespan and good dispersal ability (Boudreaux and Walters, 2006; Willan *et al.*, 2000; Lim *et al.*, 2018). *M. strigata* is considered as a euryhaline species, as it has been found from estuarine to marine environments and tolerate the salinity range from 2 to 40 ppt (Yuan *et al.*, 2010, 2016; Michael *et al.*, 2016; Rice *et al.*, 2016). Stenyakina *et al.* (2010) reported that *M. strigata* matures at a length of only 1.25 cm, while the green mussels mature at 4.5 cm, and they attain the size of 60-70 mm by end of one year (Laxmilatha, 2013). *Marcia recens*, the dominant clam species in Ashtamudi Lake matures at a length of 22 mm or at the age of 7 months (Sujitha and Nasser, 2009). Presence of young specimens of *M. strigata* throughout the year during the study indicate the multiple recruitment of larvae and this may give a competitive edge for invasive species over the native mussels and clams. These biological peculiarities, coupled with greater tolerance to varying salinities, could have been the reasons for the rapid invasion of *M. striata* all across the Ashtamudi Lake in a short span of time.

Ships and ocean transportation have been identified as one of the major source for marine species introductions world over (Keller *et al.*, 2010; Seebens *et al.*, 2013) and it has been found true for India as well (Anil *et al.*, 2002). According to Gaonkar *et al.* (2010) harbours are the gateway for introduction of non-native marine organisms in India. Over 18 species of non-native animals and plants have been documented along the Indian coasts (Anil *et al.*, 2002), though the invasive nature of many of these non-native species remains to be established. One of the non-native mollusc introduced in India is *Mytilopsis sallei* and the occurrence of this species has been recorded from major fishing harbours of India (Kalyanasundaram, 1975; Karande and Menon, 1975; Raju *et al.*, 1988; Jayachandran *et al.*, 2018). *Mytella strigata* might have been introduced into the coastal waters of India through ships and later spread to the estuaries through the smaller fishing vessels that traverse frequenty between the coastal oceanic waters and the estuaries in most of the fishing harbours of Kerala. The studies by Kauano *et al.* (2017) showed that even small fishing vessels may serve as vectors for the transfer of marine invasive species.

Anecdotal remarks of local fishers reveal that appearance of invasive mussels started after the cyclone Ockhi that struck Kerala coast in 2017. This opinion cannot be completely ruled out as Ockhi must have helped in the fast spread of the invasive mussel that might have been introduced into the Indian coast as foulers of ship or as larval forms thorugh ballast water. This also explains the presence of invasive *M. strigata* in many estuarine systems of Kerala, and can be corroborated by the absence of records of this species in earlier biodiversity surveys in Ashtamudi Lake (Divakaran *et al.*, 1981; Nair *et al.*, 1984; Santhakumari and Nair, 1984; Raghunathan, 2007; Vimalraj *et al.*, 2014; Jyothilal *et al.*, 2015; Arathi *et al.*, 2018 and Ravinesh *et al.*, 2019). According to Carlton *et al.* (2017) 289 species of living marine fauna from 16 phyla, including molluscs, have travelled thousands of kilometres through an extraordinary biological rafting on the surface of marine debris, from the Japanese coast to North American and Hawaii coast due to the a massive tsunami generated from the 2011 East Japan earthquake. This justifies the role of marine debris and massive natural forces like tsunami and cylone in transporting marine species beyond their natural distributional ranges.

As all biological invasions are well understood through population processes such as arrival, establishment, spread, and impact (Crooks and Rilov, 2009), and considering the complex interactions in marine and estuarine ecosytems and paucity of historical data (Chan and Briski, 2017; Ojaveer *et al.*, 2018), early detection of invaded species is not at all easy. In India there is also paucity of recent exploratory surveys and historial biodiversity data in the estuarine ecosystems and this is compounded by the ever increasing issue of taxonomic impediment in the country. Though marine biodiversity is such a diverse field, in many of the marine research and academic institutions there is a serious dearth of trained taxonomists in many of the marine research and academic institutions to cater to the demands of the sector, and not to speak of lesser amount of research funding available for documenting estuarine biodiversity. This may explain the failure in early detection of *Mytella strigata* in Indian waters, and possible mis-identification of species in earlier surveys. Lim *et al.* (2018) demonstrated the presence of diverse morphotypes of *M. strigata,* as in the case of this study, and this may further complicate morphological taxonomy.

Green mussel, *Perna viridis*, and the brown mussel, *P. perna*, distributed along the rocky shores support a traditional sustenance fishery in Kerala (Appukuttan *et al.*, 2001). Kollam is one of the major mussel landing centres of Kerala (Appukuttan *et al.*, 2001; Laxmilatha, 2013). In Ashtamudi Lake the newly invaded *M. strigata* has replaced the populations of Asian green mussel *Perna viridis* (Fig.6. A,B) and the present study could not locate colonies of this species once abundant in the area and supported the local fishery. Reports from Philippines (Vallejo *et al.*, 2017a,b), Singapore (Lim *et al.*, 2018) and Thailand (Sanpanich and Wells, 2019) also suggested that the native *Perna viridis* populations are gradually replaced by the invasive *M. strigata*. This study further shows the decline in the populations of other species such as the backwater oysters *Magallana bilineata* and *Saccostrea cuccullata* in Ashtamudi Lake. Similar reports of invasive *Mytella strigata* outcompeting native eastern oyster *Crassostrea virginica* through feeding competition has been reported by Galimany *et al.* (2017).

In the Ashtamudi Lake the invading mussel has formed blankets over the beds of short-neck clam (Fig. 6 C, D), which is an abundant resource in the lake. We opine that the invading *M. strigata* will eventually cause considerable negative impact to the clam fishery and to the lake ecosystem, once the species continue to proliferate in the changing climatic regimes. In Ashtamudi Lake the livelihood activities are dominated by fishing, providing employment for about 3000 people in the locality. The short-neck clam fisheries of the lake has obtained an eco-label from the Marine Stewardship Council (MSC) for the first time from India and the estimated value of fishery resources of the lake is 985 million (US$ 16.4m), with over half of the value contributed by clams (Mohamed *et al.*, 2016). The present study has showed that the invasive mussel in the Ashtamudi Lake may reach a maximum density of 11384 individuals per square meter and they inhabit both hard and soft substrata. Considering the presence of larger biomass of *M. strigata* throughout the year and their presence in higher densities in the same ecological niche of short-neck clam, it could be considered as a pest. While the invasive mussels show better larval settlement and survival rate, development of byssal nests, and higher tolerance to environmental threshholds, particularly towards salinity and turbidity, they can establish domination over the existing benthic community of short-neck clams in the lake. Though there are still intact clam beds along the lake, the dominance of *M. strigata* on the tidal channels and their fast settling in aggregations where it is able to reach high densities is a matter of concern.

The black clam *Villorita cyprinoides* is present in the low salinity regions of Ashtamudi Lake, and the invading mussels have impacted black clam fisheries. Field observations indicate that they have also replaced the non-commercial gastropods like

Fig. 6 A. Green mussel catch from Dalavapuram region, of Ashtamudi Lake in 2017; **B.** Charru mussel catch from Dalavapuram region, of Ashtamudi Lake in 2019; **C.** Occurrence of *Mytella strigata* (arrow) on short-neck clam bed in 2018; **D.** Invasion of *Mytella strigata* on short-neck clam (arrow) bed in 2019; **E.** Mangrove marshes in Ashtamudi during low tide in 2018 showing the abundance of *Pirenella cingulata*; **F.** Mangrove marshes in Ashtamudi during low tide in 2019 showing the abundance of *M. strigata*

Pirenella cingulata (Fig. 6 E, F), *Indothais blanfordi* and *Indothais lacera* from the lake. The potential for *M. strigata* to outcompete the lucrative clam fishery is a serious concern that urgently needs to be addressed, especially since replacements have been reported by authors elsewere in the world (Branch and Steffani, 2004). The abundance of invasive mussels in the lake bottom not only reduce the availability of clam resoures and impact their livelihoods, but also increase the labour of local fishers as they have to spend more time removing the invasive mussels from their harvest.

The density of *M. strigata* in Ashtamudi Lake is higher than the maximum density recorded from other areas of India such as Vembanad Lake (120 ± 24 ind. 25 cm^{-2}; Jayachandran *et al.*, 2019), Singapore (49,600 m^{-2}; Lim *et al.*, 2018), Thailand (mean density of 40,800 ± 2565 m^{-2}; Sanpanich and Wells, 2019) and south-eastern USA (11,000 m^{-2}; Spinuzzi *et al.*, 2013).

The backwaters of India harbour rich diversity of native molluscs (Subba Rao, 2017). Recent studies have shown the backwaters of Kerala harbour very interesting native molluscs (Oliver *et al.*, 2018 a, b). These native mussels living in the backwaters could well be displaced by invasive *Mytella strigata*. This would happen before we have a chance to resolve the systematics, as some of these could well be endemic to the backwaters.

Scientific reports reveal that the marine invasives such as mussels can establish well in their non-native habitats, impact ecosystem and ecosystem services, impact local biodiversity, outcompete native species, introduce diseases and parasites, impact the productivity of fisheries, interfere with industrial facilities, shipping and port maintenance and threaten aquaculture operations (Johnson and Chapman, 2007; Stafford *et al.*, 2007; Molnar *et al.*, 2008; Wells *et al.*, 2009; Crowe and Frid, 2015). Reports from southeast Asia have already demonstrated that *Mytella strigata* is an emerging marine invasive species, inflicting a series of threats to ecosystem and biodiversity. Presence of young and mature mussels throughout the year, rapid expansion of population and socio-economic and environmental implications could place *M. strigata* as one of the imminent threats to Ashtamudi Lake. Further studies are warranted to establish and attempt to negate the impact of invasive *M. strigata* on native biodiversity, ecosystem services and biogeochemical cycles. As Ashtamudi is considered as the gateway for the other estuaries in Kerala, they may also serve as a hub in transmission of invasive species to other water bodies. In India the presence of this invasive species has been reported only from the Kerala coast thus far. Considering the presence of larger harbours elsewhere in east and west coasts of India, there is an urgent need to identify the presence of *M. strigata* in the country by locating the pathways of introduction, promoting studies on invasion biology, and strengthening awareness on marine invasive species as an essential tool for management initiatives. There are not many success stories of eradication of marine invasive species in natural water bodies and therefore, adopting a precautionary principle of extensive surveys, research and better enactment of regulations are essential towards management.

ACKNOWLEDGEMENTS

We thank the traditional fishers of Ashtamudi Lake, specifically Mr. Rajan and Mr. Robin, for their support in surveys, which made the work possible. We are thankful to the research scholars Smrithy Raj and Akhil Ignus for their support in field work.

REFERENCES

Anil, A.C., Venkat, K., Sawant, S.S., Dileepkumar, M., Dhargalkar, V.K., Ramaiah, N., Harkantra, S.N. and Ansari, Z.A. 2002. Marine bioinvasion: Concern for ecology and Shipping. *Current Science*, 83 (3): 214-218.

Appukuttan, K.K., Mohamed, K.S., Kripa, V., Ashokan, P.K., Anil, M.K., Sasikumar, G., Velayudhan, T.S., Laxmilatha, P., Said Koya, K.P., Radhakrishnan, P., Joseph, M., Alloycious, P.S., Surendranathan, V.G., Sivadasan, M.P., Nagaraja, D., Sharma, J. and Naik, S.M. 2001. Survey of green mussel seed resources of Kerala and Karnataka. *Marine Fisheries Information Service*, 168: 12-19.

Arathi, A.R., Oliver, P.G., Ravinesh. R., and Biju Kumar, A. 2018. The Ashtamudi Lake short-neck clam: re-assigned to the genus *Marcia* H. Adams & A. Adams, 1857 (Bivalvia, Veneridae). *ZooKeys*, 799: 1–20.

Benson W.H. 1842. Mollusca. in: T. Cantor, General features of Chusan, with remarks on the flora and fauna of that island. *Annals and Magazine of Natural History*. 1, (9): 486-490.

Boehs, G., Absher, T.M., and Cruz-Kaled, A.D. 2004. Composition and distribution of benthic molluscs on intertidal flats of Paranaguá Bay (Paraná, Brazil). *Scientia Marina*, 68 (4): 537-543.

Boudreaux, M.L. and Walters L.J. 2006. *Mytella charruana* (Bivalvia: Mytilidae): a new, invasive bivalve in Mosquito Lagoon, Florida. *Nautilus,* 120: 34–36.

Branch, C.G. and Steffani, N. 2004. Can we predict the effects of alien species? A case-history of the invasion of South Africa by *Mytilus galloprovincialis* (Lamarck). *Journal of Experimental Marine Biology and Ecology*, 300, (1-2): 189-215.

Buschbaum, C., Dittmann, S., Hong, J., Hwang, I., Strasser, M., Thiel, M., Valdivia, N., Yoon, S. and Reise, K. 2009. Mytilid mussels: global habitat engineers in coastal sediments. *Helgoland Marine Research*, 63: 47–58.

Carlton, J.T. 1996. Biological invasions and cryptogenic species. *Ecology*, 77: 1653– 1655.

Carlton, J.T., Chapman, J.W., Geller, J.B., Miller, J.A., Carlton, D.A., McCuller, M.I., Treneman, N.C., Steves, B.P. and Ruiz, G.M. 2017. Tsunami-driven rafting: Transoceanic species dispersal and implications for marine biogeography, *Science,* 357, I6358: 1402-1406.

Chan, F.T. and Briski, E. 2017. An overview of recent research in marine biological invasions. *Marine Biology*, 164, 121: 1-10.

Coan, E.V. and Scott, P.V. 2012. *Bivalve seashells of tropical West America. Marine bivalve mollusks from Baja California to northern Peru*. 2 vols, 1258 pp.

Crooks, J.A. and Rilov, G. 2009. The establishment of invasive species. In:Rilov, G. and Crooks J.A. (eds.), *Biological Invasions in Marine Ecosystems,* Springer-Verlag, Berlin. 173–175.

Crowe, T.P. and Frid, C.L.J. 2015. *Marine Ecosystems: Human Impacts on Biodiversity, Functioning and Services*. Cambridge University Press, UK, 397 pp.

Darrigrán, G.Y. and Lagreca, M. 2005. *Moluscos litorales del estuario del río de la Plata, Argentina*. ProBiota, FCNyM y UNLP, Serie Técnica Didáctica No. 8, Buenos Aires. 41 pp.

Divakaran, O., Murugan, T. and Nair, N.B. 1981. Distribution and seasonal variation of the benthic fauna of the Ashtamudi Lake, South-West coast of India. *Mahasagar,* 14(3): 167-172.

d'Orbigny, A. 1846. *Mollusques. Lamellibranches. Familledes Mytilidae. In: Voyage dans l'Amerique Méridionale*. PitoitLevrault et Cie., Paris, Strasbourg, 5 (3): 489-758.

Galil, B.S., Marchini, A., Occhipinti-Ambrogi, A., Minchin, D., Naršèius, A., Ojaveer, H. and Olenin, S. 2014. International arrivals: widespread bioinvasions in European Seas. *Ethology Ecology and Evolution*, 26: 152-171.

Galimany, E., Lunt, J., Freeman, C.J., Reed, S., Iris, S. and Paul, V.J. 2017. Feeding behaviour of eastern oysters *Crassostrea virginica* and hard clams *Mercenaria mercenaria* in shallow estuaries. *Marine Ecology Progress Series*. 567:125–137. https://doi.org/10.3354/meps12050

Gaonkar, C., Sawant, S.S., Anil, A.C., Venkat, K. and Harkantra, S.N. 2010. Mumbai harbour, India: Gateway for introduction of marine organisms. *Environmental monitoring and assessment,* 163: 583-589.

Gillis, N.K., Walters, L.J., Fernandes, F.C. and Hoffman, E.A. 2009. Higher genetic diversity in introduced than in native populations of the mussel *Mytella charruana*: evidence of population admixture at introduction sites. *Diversity and Distributions,* 15: 784–795.

GISD, Global Invasive Species Database. 2019. *Musculista senhousei*. http://issg.org/database/species/ecology.asp?si=1031&fr=1&sts=&lang=EN

Hanley, S.C.T. 1843. Descriptions of five new species of bivalve shells, from the collection of W. Metcalfe, Esq. *Proceedings of the Zoological Society of London,* 11: 101-102.

Huber, M. 2010. *Compendium of bivalves. A full-color guide to 3,300 of the world's marine bivalves. A status on Bivalvia after 250 years of research*. ConchBooks, Hackenheim, 901 pp.

Jayachandran, P.R., Jima, M., Philomina Joseph, Sanu, V.F. and Bijoy Nandan, S. 2018. Invasion of biofouling mussel *Mytilopsis* Conrad, 1857 (Bivalvia: Dreissenacea) in the Cochin backwaters, southwest coast of India. *Current Science,* 115: 2198–2200.

Jayachandran, P.R., Aneesh, B.P., Oliver, P.G., Philomina, J., Jima, M., Harikrishnan, K. and Bijoy Nandan, S. 2019. First record of the alien invasive biofouling mussel *Mytella strigata* (Hanley, 1843) (Mollusca: Mytilidae) from Indian waters. *BioInvasions Records*, 8: 828–837.

Johnson, C.R. and Chapman, A.R.O. 2007. Seaweed invasions: introduction and scope. *Botanica Marina* 50: 321–325. DOI 10.1515/BOT.2007.037

Jyothilal, C.S., Bennopereira, F.G., Sumesh, C., Sachin, S.R. and BinilShijith, V. 2015. Stake net Catch analysis of Ashtamudi Lake. *International Journal of Aquaculture,* 5 (14): 1-5.

Kalyanasundaram, N. 1975. Studies on the biology of *Mytilopsis sallei* (Recluz), an important marine fouling mollusc. *Bulletin of the Department of Marine Science,* University of Cochin, 7: 658–693.

Karande, A.A. and Menon, K.B. 1975. *Mytilopsis sallei,* a fresh immigrant in Indian harbours. *Bulletin Department of Marine Science*, University of Cochin, 7, 455–466.

Kauano, R.V., Roper, J.J. and Rocha, R.M. 2017. Small boats as vectors of marine invasion: experimental test of velocity and desiccation as limits. *Marine Biology,* 164: 27, 1-10. https://doi.org/10.1007/s00227-016-3057-x

Keller, H., Borke, J., Chaudhary, N., Lamm, B. and Kleis, A. 2010. Continuity in Parenting Strategies: A Cross-Cultural Comparison. *Journal of Cross-Cultural Psychology*, 41 (3): 391–409.

Laxmilatha P. 2013. A review of the green mussel *Perna viridis* fishery of south west coast of India. *International Journal of Marine Science,* 3: 408-416.

Lim, J.Y., Tay, T.S., Lim, C.S., Lee, S.S.C., Teo, S.L.M. and Tan, K.S. 2018. *Mytella strigata* (Bivalvia: Mytilidae): an alien mussel recently introduced to Singapore and spreading rapidly. *Molluscan Research*, 38: 170–186.

Mediodia, D.P., De Leon, S.M.S., Anasco, N.C. and Baylon, C.C. 2017. Shell morphology and anatomy of the Philippine charru mussel *Mytella charruana* (d'Orbigny, 1842). *Asian Fisheries Science,* 30: 185–194.

Michael, A.R., Paul, D.R., Ashley, D.S. and Westly, R.R. 2016. Identification and salinity tolerance of the Western Hemisphere mussel *Mytella charruana* (d'Orbigny, 1842) in the Philippines. *Journal of Shellfish Research,* 35: 865–873.

Mohamed, K.S., Kripa, V., Narayankumar, R., Prema, D., Venkatesan, V., Malayilethu, V., Sharma, J. and Sajikumar, K.K. 2016. *Assessment of Eco-labelling as Tool for Conservation and Sustainable Use of Biodiversity in Ashtamudi Lake, Kerala*. The Economics of Ecosystems and Biodiversity India Initiative. GIZ India, TEEB.

Molnar, J.L., Gamboa, R.L., Revenga, C. and Spalding, M.D. 2008. Assessing the global threat of invasive species to marine biodiversity. *Frontiers in Ecology and the Environment,* 6: 485– 492.

Nair, N.B., Aziz, P.K.A., Arunachalam, M., Dharmaraj, K. and Krishnakumar, K. 1984. Ecology of Indian Estuaries. Ecology and distribution of benthic macrofauna in the Ashtamudi Estuary, Kerala. *Mahasagar*, 17 (2): 89 - 101.

Occhipinti-Ambrogi,A. and Galil, B.S. 2004. A uniform terminology on bioinvasions: a chimera or an operative tool? *Marine Pollution Bulletin,* 49: 688–694.

Ojaveer, H., Galil, S.B., Carlton, J.T., Alleway, H., Goulletquer, P., Lehtiniemi, M., Marchini, A., Miller, W., Ambrogi, A.O., Peharda, M., Ruiz, G.M., Williams, S.L. and Zaiko, A. 2018. Historical baselines in marine bioinvasions: Implications for policy and management. *PLoS ONE*, 13 (8), 1-48. https://doi.org/10.1371/journal.pone.0202383

Oliver, P.G., Jayachandran, P.R. and Nandan, S.B. 2018a. *Cuspidaria cochinensis* Preston, 1916 transferred to the Corbulidae (Mollusca, Bivalvia) and assigned to the genus *Cuneocorbula*. *Marine Biodiversity*, 48:1223–122. DOI 10.1007/s12526-016-0578-y

Oliver, P.G., Hallan, A., Jayachandran, P.R., Joseph, P., Sanu, V.F., Bijoy Nandan, S. 2018b. Taxonomy of myid bivalves from fragmented brackish-water habitats in India, with a description of a new genus *Indosphenia* (Myida, Myoidea, Myidae). *ZooKeys*, 799: 21–46.

Orbigny, A.C.V.D. de. 1842. Voyage dans l' Amerique m6ridionale (Le Bresil, La republiqueorientale de l'Uruguay, la republique Argentine, La Patagonie, la republique du Chili, la republique de Bolivia, la rt5publique du Perou), execute pendant les annees 1826 1827 1828 18291830 1831 1832 et 1833. Tome Cinquieme, 3.e Partie: Mollusques. V. Levrault, Paris.

Rafinesque, C.S. 1815. Analyse de la Nature ou Tableau de l'Univers et des Corps organisés. Palerme: 1-224.

Raghunathan M.B. 2007. *Faunal Diversity of Ashtatnudi Wetlands, Kerala, India*. Record of Zoological Survey of India, Occasional Paper 276, Kolkatta, 38pp.

Raju, G.J.V.J., Rao, K.S. and Viswanadham, B. 1988. *Marine Biodeterioration*. In: (Thompson, M. F., Sarojini, R. and Nagabhushanam, R. (eds.), *Advanced Techniques Applicable to the Indian Ocean*, Oxford and IBH, New Delhi. 513–525.

Ravinesh, R., Anjana, V.L., Arathi, A.R., and Biju Kumar, A. 2019. *Molluscan fauna of Asthamudi Lake, Kerala, India*, In: Junaid, H. and Salom, G.T., (eds.), *National Seminar on Environmental Status of Estuarine and Coastal Ecosystems in India*, ECEI-2019 Department of Environmental Sciences, University of Kerala, India, 176-178.

Rice, M.A., Rawson, P.D., Salinas, A.D. and Rosario, W.R. 2016. Identification and salinity tolerance of the western hemisphere mussel *Mytella charruana* (d'Orbigny, 1842) in the Philippines. *Journal of Shellfish Research*, 35: 865–873.

Sanpanich, K. and Wells, F.E. 2019. *Mytella strigata* (Hanley, 1843) emerging as an invasive marine threat in Southeast Asia. *BioInvasions Records,* 8: 343–356.

Santhakumari, V. anmd Nair, N.B. 1984. Vertical distribution of Marine Wood boring and Fouling Organisms from the Estuarine Areas of the South West Coast of India. *Fishery Technology,* 21: 118-125.

Scarabino, V., Maytía, S. and Cachés, M. 1975. Carta bionómicalitoral del departamento de Montevideo I.

Nivelessuperiores del sistemalitoral. *Comunicaciones de la Sociedad Malacológica del Uruguay*, 4 (29): 117-126.

Scarlato, O.A. and Starobogatov, Y.I. 1979. *Osnovye cherty evoliutsii i sistema klassa Bivalvia [General evolutionary patterns and the system of the Class Bivalvia]. In Y. I. Starobogatov, ed., Morfologiia, Sistematika i Filogeniia Molliuskov [Morphology, Systematics and Phylogeny of Mollusks].* AkademiiaNauuk SSSR, Trudy Zoologicheskogo Instituta 80:5–38. In Russian. For English translation, see Boss K.J. and Jacobson, M.K. 1985, Museum of Comparative Zoology, Harvard University, Department of Mollusks, Special Occasional Publication. 5: 1–67.

Seebens, H., Gastner, M., and Blasius, B. 2013. The risk of marine bioinvasion caused by global shipping. *Ecology Letters*, 16 (6): 782-790.

Soot-Ryen, T.1955. *A report on the family Mytilidae (Pelecypoda). University of Southern California*, Allan Hancock Foundation, Allan Hancock Pacific Expeditions, 20 (1): 261 pp.

Spinuzzi, S., Schneider, K.R., Walters, L.J., Yuan, W.S. and Hoffman, E.A. 2013. Tracking the distribution of non-native marine invertebrates (*Mytella charruana, Perna viridis* and *Megabalanus coccopoma*) along the south-eastern USA. *Marine Biodiversity Records*, 6; e55; 1-13. doi:10.1017/S1755267213000316

Stafford, H., Willan, R.C. and Neil, K.M. 2007. The invasive Asian Green Mussel, *Perna viridis* (Linnaeus, 1758) (Bivalvia: Mytilidae), breeds in Trinity Inlet, tropical northern Australia. *Molluscan Research*, 27: 105-109.

Stenyakina, A., Walters, L,J., Hoffman, E.A. and Calestani, C. 2010. Food availability and sex reversal in *Mytella charruana*, an introduced bivalve in the southeastern United States. *Molecular Reproduction and Development*, 77: 222–230.

Suchanek, T.H. 1986. Mussels and their role in structuring rocky shore communities. In: Moore, P.G. and Seed, R. (eds.), *The Ecology of Rocky Coasts* Columbia University Press, New York, 70–96.

Sujitha, T. and Nasser, M 2009. Growth and population dynamics of short-neck clam *Paphia malabarica* from Dharmadom estuary, North Kerala, southwest coast of India. *Journal of the Marine Biological Association of India*, 51 (1): 87-92.

Vallejo, B. Jr., Conejar-Espedido, J. and Manubag, L. 2017a. The Ecology of an incipient marine biological invasion: The Charru Mussel *Mytella charruana* d'Orbignyi, 1846 (Bivalvia: Mytilidae) in Manila Bay, Luzon, Philippines. *Philippine Journal of Science*, 146 (4): 483-492.

Vallejo, B. Jr., Conejar-Espedido, J., Manubag, L., Artiaga, K.C.C., Damatac II, A.M., Imperial, I.C.V.J., Itong, T.A.B., Fontanilla, I.K. and Cao, E.P. 2017b. First record of the Charru mussel *Mytella charruana* d'Orbigny, 1846 (Bivalvia: Mytilidae) from Manila Bay, Luzon, Philippines. *BioInvasions Records,* 6: 49–55.

Vimalraj, R.V., Raju, B., Soumya, W., Shibu, A., Lekshmi, S., Vardhanan, S.Y., Sruthi, S. and Radha Krishnan, T. 2014. Aquatic bioresources of Ashtamudi Lake, Ramsar site, Kerala. *Journal of Aquartic Biology and Fisheries*, 2(1): 297-303.

Willan, R.C., Russell, B.C., Murfet, N.B., Moore, K.L., McEnnulty, F.R., Horner, S.K., Hewitt, C.L., Dally, G.M., Campbell, M.L. and Bourke S.T. 2000. Outbreak of *Mytilopsis sallei* (Récluz, 1849) (Bivalvia: Dreissenidae) in Australia. *Molluscan Research*, 20: 25-30.

Wells, F., McDonald, J. and Huisman, J. 2009. Introduced marine species in Western Australia. Department of Fisheries, Perth Fisheries Occasional Publications No. 57: 1–97

Winder, M., Jassby, A.D. and Nally, R.M. 2011. Synergies between climate anomalies and hydrological modifications facilitate estuarine biotic invasions. *Ecology Letters*, 14: 749–757.

Yuan, W., Walters, L., Schneider, K. and Hoffman, E. 2010. Exploring the survival threshold: a study of salinity tolerance of the non-native mussel *Mytella charruana*. *Journal of Shellfish Research*, 29: 415–422.

Yuan, W., Walters, L.J, Brodsky, S.A., Schneider, K.R and Hoffman, E.A. 2016. Synergistic effects of salinity and temperature on the survival of two nonnative bivalve molluscs, *Perna viridis* (Linnaeus 1758) and *Mytella charruana* (d'Orbigny 1846). *Journal of Marine Biology*, 1-14. http://dx.doi.org/10.1155/2016/9261309