Research Article

Status of the invasive charru mussel *Mytella strigata* (Hanley, 1843) in the upper Gulf of Thailand five years after it was first surveyed

Fred E. Wells¹,², Teerapong Duangdee³, Kitithorn Sanpanich⁴ and Sherralee S. Lukehurst¹

¹School of Molecular and Life Sciences, Curtin University, Kent Street, Bentley, WA 6102 Australia
²Negaunee Integrative Research Center, Field Museum of Natural History, Chicago, Illinois 60605 USA
³Department of Marine Science, Faculty of Fisheries, Kasetsart University, Bangkok, Thailand
⁴Retired from Institute of Marine Science, Burapha University, Chonburi, Thailand

Corresponding author: Fred E. Wells (fred.wells@curtin.edu.au)

Abstract

The invasive charru mussel *Mytella strigata* (Hanley, 1843) was first reported by fishermen in the upper Gulf of Thailand in 2017 and was scientifically surveyed in November 2018. A survey in August 2023 demonstrated that the mussel had not spread significantly in the region in nearly five years. Populations remained dense in aquaculture ponds and the Bangpakong River estuary where it was most abundant in 2018, but *M. strigata* occurred at only one of 10 rocky shore sites on the open coast. Size frequency histograms for all populations of *M. strigata* sampled were unimodal, suggesting there was one spawning season, but settlement apparently occurred at different times at the various sites. At sites where *M. strigata* occurred with the Asian green mussel *Perna viridis* (Linnaeus, 1758), the evidence that *M. strigata* was outcompeting *P. viridis* was uncertain. Data obtained during the 2018 and 2023 surveys provide a sound basis for monitoring the status of *M. strigata* in the upper Gulf of Thailand in the future. There is an urgent requirement to undertake basic biological research on population parameters such as reproductive periodicity, growth rates and, in particular, the environmental and economics of the widespread invasion of this species.

Key words: *Perna viridis*, invasive marine species, marine pests, Mytilidae, competition, bivalves

Introduction

Invasive marine species (IMS; also known as introduced marine pests) are one of the most important anthropogenic threats to marine ecosystems (Katsanevakis et al. 2014; Crowe and Frid 2015; McDonald et al. 2020; Salimi et al. 2021). They have a wide variety of potential adverse effects, including: introducing human and other diseases (Hallegraeff et al. 1988); displacing native species through predation or competition (Arcella et al. 2014; Branch and Steffani 2004); damaging local habitats (Robinson et al. 2007); changing the ecology of native communities (Colautti and Lau 2015; Rius et al. 2015) either directly or through cascading community-level impacts (Griffiths et al. 1992; Shine 2010); and clogging pipes and damaging critical marine infrastructure (Wells et al. 2009).
While IMS occur in a wide variety of taxa, a large number are in the molluscan bivalve family Mytilidae (mussels). The high fecundity, rapid growth rate and planktotrophic larval stage make many mussels excellent species for aquaculture. Unfortunately, these same characteristics also make them excellent potential IMS (Branch and Steffani 2004).

Perhaps the most widespread introduced mussel is the European *Mytilus galloprovincialis* (Lamarck, 1819), which is listed by the IUCN as one of the 100 worst invasive species in the world (Lowe et al. 2004). Although there are eight species in the genus *Mytilus* (WoRMS 2023), *M. galloprovincialis* appears to be the only one to become invasive. It is native to the Atlantic coast of southern Europe and the Mediterranean Sea. The hundreds of years of wooden boats leaving this region to explore other continents has led to the widespread introduction of *M. galloprovincialis* in other temperate localities, including western North America, Asia, South Africa, Australia and New Zealand (NEMESIS 2023). The introductions are subtle as the species closely resembles others in the genus and they can often be detected only through DNA sequencing (Dias et al. 2014; Popovic et al. 2020).

Other invasive mytilids include the Red Sea *Brachidontes pharaonis* (P. Fischer, 1870) that invaded the eastern Mediterranean through the Suez Canal shortly after it was opened in 1869 (e.g. Rilov et al. 2004; Dogan et al. 2007), the Australian *Xenostrobus securis* (Lamarck, 1819) which has invaded Hong Kong (Astudillo et al. 2014, 2017) and the western Mediterranean (Barbieri et al. 2011). The Asian *Arcuatula senhousia* (W.H. Benson, 1842) has been reported in widely separated regions such as New Zealand (Willan 1985), Western Australia (Slack-Smith and Brearley 1987) and California (Crooks 2002). *Perna viridis* (Linnaeus, 1758), the Asian green mussel, is native to the Indo-Pacific region between the Persian Gulf to the Philippines, including peninsular Malaysia and the Indonesian islands of Sulawesi, Sumatra and Java (Siddall 1980). It has been distributed widely in the Pacific islands both deliberately for aquaculture and accidentally through vessels, even reaching the Caribbean Sea (Agard et al. 1992; Barber et al. 2005). Oddly, although *P. viridis* has been regarded as posing a considerable IMS threat to Australia, it has never established permanently on the continent (Heersink et al. 2014; Wells 2017). A small population was detected in Cairns, Queensland in 2001 but died out naturally after a few years (Stafford et al. 2007). The congeneric *P. perna* (Linnaeus, 1758) is native to the western Indian Ocean and the east coast of Africa, but has been introduced to the Gulf of Mexico, west coast of Africa and east coast of South America (NEMESIS 2023).

The populations of these mussels are not necessarily static; they may rapidly develop dense populations that suddenly crash. Sometimes the reasons for the population declines are apparent. For example, *A. senhousia* developed substantial populations in the Swan River, Western Australia in the 1980s. These thrived for years but were apparently wiped out by an
unseasonal intense rainfall in the Austral summer of 2000 (McDonald and Wells 2010). It may have since been reestablished (Cottingham et al. unpublished). *Perna perna* had a dense population in Haifa, Israel in early 2021 that was exterminated by a marine heat wave later that year (Galil et al. 2022). The decline and elimination of *P. viridis* in Cairns was described above but the reasons for its demise are not known. *Mytilus galloprovincialis* invaded Langebaan Lagoon in South Africa, but subsequently died off (Robinson et al. 2007).

*Mytella strigata* (Hanley, 1843) (=*M. charruana* (d’Orbigny, 1842)) is a recent addition to the list of invasive mussels. The species is native to both coasts of Central and South America (Lim et al. 2018). It was first reported in the southeastern United States in 1986 and has since become widespread in Florida and Georgia (Boudreaux and Walters 2006; Spinuzzi et al. 2013; Calazans et al. 2017) and has recently been recorded from the Caribbean coast of Venezuela (Lodeiros et al. 2021).

Chavanich et al. (2010) published a detailed study of invasive marine species in southeast Asia. About the same time, Sanpanich (2011) surveyed the bivalves on the east coast of the Gulf of Thailand. Neither recorded *M. strigata*. The first record of *M. strigata* in Southeast Asia was made by Rice et al. (2016) in the Philippines (as *M. charruana*) and two Philippine reports rapidly followed: Mediodia et al. (2017) and Vallejo et al. (2017). Lim et al. (2018) provided a detailed analysis of the taxonomy and morphology of the species and determined its proper name was *M. strigata*. Further Philippine records were subsequently published by Fabiosa et al. (2021) and Fuertes et al. (2021). In the seven years since the first Southeast Asian record of *M. strigata* the species has been found in a number of geographically separated countries, including Singapore (Lim et al. 2018), India (Jayachandran et al. 2019; Ravinesh et al. 2023), Taiwan (Huang et al. 2021) and Guangdong, Hainan and Hong Kong in China (Ma et al. 2022; Joyce et al. 2023; Yu et al. 2023).

The first reports of *M. strigata* in Thailand were in October 2017, when local *Perna viridis* farmers in Samut Prakan Province in the upper Gulf of Thailand were concerned that an unidentified mussel was outcompeting the Asian green mussel. This prompted surveys in 2018 to determine the extent of the species (Sanpanich and Wells 2019). Wangkulangkul et al. (2022) recently reported *M. strigata* from the Songkla Lakes in the southwestern part of the Gulf of Thailand.

The present paper investigates *M. strigata* in the upper Gulf of Thailand five years after the first survey to determine whether the species is still occurring in the region and whether its range has expanded.

**Materials and methods**

Twenty sites in the upper Gulf of Thailand were surveyed for *M. strigata* in August 2023, including most of the sites examined by Sanpanich and Wells
Figure 1. Map of sites sampled for *Mytella strigata* in the upper Gulf of Thailand in August 2023. Map prepared by Kitithorn Sanpanich using Google Earth. Closed circles indicate that the species was present, open circles indicate that the species was absent.

(2019). The survey commenced at Bang Saen (Site 1) in Chonburi Province on the eastern side of the upper gulf (Figure 1; Table 1). At all sites on the open coast, rocky shores were searched for mussels on low spring tides. A boat was used at Si Racha (Site 2) to inspect four commercial *Perna viridis* aquaculture lines for mussels.

The survey progressed southwards to Kungkrabaen Bay, where a site on the rocky headland on the open coast on northern side of the bay was surveyed (Site 6), then a rocky shore on the western side of the bay (Site 7). Two sites were examined at the aquaculture demonstration facility: a rocky shore and rock wall near the base of the jetty (Site 8) and oysters growing on aquaculture demonstration ropes (Site 9). An additional open shore rocky site was included at Pattaya (Site 10) on drive north back to Bang Saen.

A small boat was hired to survey the three 2018 sites at the mouth of the Bangpakong River. However, sea conditions were too rough to reach the sites, so instead three nearby sites (Sites 11–13) in the river were surveyed. Sites on the western side of theinner Gulf of Thailand were then examined. As far as possible, these were the same as in 2018. Most importantly the aquaculture ponds at Prachuap Kiri Khan Coastal Aquaculture Research and Development Center, Klongwarn (Site 15) and the Marine and Coastal Resources Research and Development Centre (Upper Gulf of Thailand), Samut Sakhon Province (Site 20). All shoreline sites sampled were intertidal. Mussel lines, ropes in the Bangpakong River and the aquaculture ponds were sampled at depths of up to 3 m. Sites were sampled for approximately one hour.
Table 1. Locations surveyed for *Mytella strigata* in the inner Gulf of Thailand. Species detected: *Mytella strigata*, *Perna viridis*, *Byssogerdius subsulcatus*, *Modiolus* sp., *Septifer* sp. NS, not surveyed.

<table>
<thead>
<tr>
<th>Site no.</th>
<th>Location</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Date</th>
<th>Habitat</th>
<th>Mussel species detected</th>
<th><em>M. strigata</em> in 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bang Saen Beach</td>
<td>13.300</td>
<td>100.900</td>
<td>1 Aug 2023</td>
<td>Rocky shore on open coast</td>
<td>Patches of <em>M. strigata</em> &lt; 10 mm</td>
<td>NS</td>
</tr>
<tr>
<td>2</td>
<td>Kasetsart University Fisheries Research Center, Si Racha</td>
<td>13.179</td>
<td>100.921</td>
<td>1 Aug 2023</td>
<td>Hanging ropes</td>
<td><em>M. strigata, P. viridis, B. subsulcatus, Modiolus</em> sp., <em>Septifer</em> sp.</td>
<td>YES</td>
</tr>
<tr>
<td>3</td>
<td>Samaesan</td>
<td>12.599</td>
<td>100.949</td>
<td>2 Aug 2023</td>
<td>Rocky shore on open coast</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>4</td>
<td>Ta Kuan Beach</td>
<td>12.672</td>
<td>101.165</td>
<td>2 Aug 2023</td>
<td>Hanging ropes</td>
<td><em>M. strigata, P. viridis</em> washed up from offshore mussel farm. <em>B. subsulcatus, Modiolus</em> sp. live on rocks.</td>
<td>NS</td>
</tr>
<tr>
<td>5</td>
<td>Mae Rum Peung Beach</td>
<td>12.611</td>
<td>101.384</td>
<td>2 Aug 2023</td>
<td>Rocky shore on open coast</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>6</td>
<td>Hin Khrong, north of Kungkrabaen Bay</td>
<td>12.608</td>
<td>100.982</td>
<td>2 Aug 2023</td>
<td>Rocky shore on open coast</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>7</td>
<td>Mouth of Kungkrabaen Bay</td>
<td>12.587</td>
<td>101.165</td>
<td>3 Aug 2023</td>
<td>Rocky shore on open coast</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>8</td>
<td>Southern Kungkrabaen Bay</td>
<td>12.581</td>
<td>101.192</td>
<td>3 Aug 2023</td>
<td>Rocky shore and wall in bay</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>9</td>
<td>Kungkrabaen Bay, Sea Farming Demonstration Unit</td>
<td>12.582</td>
<td>101.892</td>
<td>3 Aug 2023</td>
<td>Hanging ropes in bay</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>10</td>
<td>Pattaya</td>
<td>12.974</td>
<td>100.890</td>
<td>4 Aug 2023</td>
<td>Rocky shore and wall on open coast</td>
<td><em>B. subsulcatus, Modiolus</em> sp., dead <em>P. viridis</em></td>
<td>NS</td>
</tr>
<tr>
<td>11</td>
<td>Bangpakong River: Bird Island</td>
<td>13.496</td>
<td>100.982</td>
<td>5 Aug 2023</td>
<td>Hanging rope in river</td>
<td><em>M. strigata, P. viridis</em></td>
<td>YES</td>
</tr>
<tr>
<td>12</td>
<td>Bangpakong River: Fisherman’s House</td>
<td>13.503</td>
<td>100.981</td>
<td>5 Aug 2023</td>
<td>Jetty in river</td>
<td><em>M. strigata, P. viridis</em></td>
<td>YES</td>
</tr>
<tr>
<td>13</td>
<td>Bangpakong River: Bangpakong Bridge</td>
<td>13.485</td>
<td>101.003</td>
<td>5 Aug 2023</td>
<td>Jetty in river</td>
<td><em>M. strigata, P. viridis</em></td>
<td>YES</td>
</tr>
<tr>
<td>14</td>
<td>Klongwan Pier</td>
<td>11.736</td>
<td>99.782</td>
<td>6 Aug 2023</td>
<td>Jetty on open coast</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>15</td>
<td>Prachuap Kiri Khan Coastal Aquaculture Research and Development Center, Klongwan</td>
<td>11.750</td>
<td>99.792</td>
<td>6 Aug 2023</td>
<td>Mud bottom on side of aquaculture pond</td>
<td><em>M. strigata</em></td>
<td>YES</td>
</tr>
<tr>
<td>16</td>
<td>Khao Ta Mong Lai Forest Park</td>
<td>11.837</td>
<td>99.830</td>
<td>6 Aug 2023</td>
<td>Rocky shore on open coast</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>17</td>
<td>Sirinath Rajini Mangrove Ecology Learning Center</td>
<td>12.393</td>
<td>99.982</td>
<td>7 Aug 2023</td>
<td><em>Rhizophora</em> mangroves</td>
<td>None</td>
<td>NO</td>
</tr>
<tr>
<td>18</td>
<td>Kao Ta Kiep</td>
<td>12.514</td>
<td>99.981</td>
<td>7 Aug 2023</td>
<td>Jetty on open coast</td>
<td>None</td>
<td>NS</td>
</tr>
<tr>
<td>19</td>
<td>Institute of Marine Science, Burapha University (Cha Am)</td>
<td>12.872</td>
<td>100.018</td>
<td>8 Aug 2023</td>
<td>Rock wall on open coast</td>
<td>None</td>
<td>NO</td>
</tr>
<tr>
<td>20</td>
<td>Marine and Coastal Resources Research and Development Centre (Upper Gulf of Thailand, Samut Sakhon Province)</td>
<td>13.502</td>
<td>100.270</td>
<td>8 Aug 2023</td>
<td>Mud bottom on side of aquaculture pond</td>
<td><em>M. strigata</em></td>
<td>YES</td>
</tr>
</tbody>
</table>

Other mytilid mussel species found during the survey were also recorded. Salinity at selected sites was measured with a hand held refractometer. Individuals of both *M. strigata* and *P. viridis* were measured using digital callipers at the Bangpakong River sites (11–13) and the aquaculture pond sites (15 and 20). *t*-tests were made of the mean shell lengths of *M. strigata* and *P. viridis* at the three sites in the Bangpakon River (Sites 11 to 13) and *M. strigata* in the two aquaculture ponds at Samut Sakhon (Site 20).
Results

Distribution of Mytella strigata in the upper Gulf of Thailand in August 2023

The distribution of *M. strigata* in the upper Gulf of Thailand in August 2023 is shown on Figure 1 and in Table 1. The species was found across the upper gulf from Prachuap Kiri Khan (Site 15) in the west to Ta Kuan Beach (Site 4), in the east. The distribution in 2023 was essentially the same as in 2018. The southernmost western site in 2018 was also Prachuap Kiri Khan (Site 15). Kasetsart University operates a small aquaculture facility a few hundred metres away. Although we did not sample the KU ponds, staff told us the mussels have invaded the ponds. However, *M. strigata* was not found on the nearby Klongwan Pier on the open coast (Site 14). The southernmost eastern site where *M. strigata* was detected in 2023 at Ta Kuan Beach (Site 4) was not sampled in 2018. It is approximately 77 km south of the southernmost 2018 record at Si Racha (Site 2).

The mussels were present at only 8 of the 20 sites surveyed. The species was found at two aquaculture ponds (Sites 15 and 20) and the *Perna viridis* hanging ropes at Si Racha (Site 2) where it was also found in 2018. *Mytella strigata* occurred in clumps at the three sites in the Bangpakong River: on a rope hanging from the jetty at Bird Island (Site 11; Figure 2) and on jetties in the river (Sites 12 and 13). Salinities at the sites were 16 PSU at Bird Island and the Fisherman’s hut and 14 PSU at the bridge. The only open rocky shore where *M. strigata* occurred was at Bang Saen (Site 1), which is close to the dense populations recorded near the mouth of the Bangpakong River. There was a hanging rope mussel farm approximately 50 m offshore...
at Ta Kuan Beach (Site 4). Fresh dead shells of both *Mytella strigata* (including tissues) and *P. viridis* from the mussel farm were washed up on the beach, but no live individuals of either species were found on the intertidal rock causeway.

The intertidal rocks at Bang Saen Beach (Site 1) were not sampled in 2018, but the population was detected early in 2019. Initial plans were to monitor the development of the population but this was discontinued when movement restrictions were imposed during the covid pandemic (K. Sanpanich pers. obs.). When sampled in 2023 the population consisted of dense aggregations of small (< 10 mm) mussels in small patches in depressions in the rocks.

In 2018 small numbers of *M. strigata* were found on *Perna viridis* aquaculture lines at Si Racha (Site 2); low numbers were also detected in 2023. The lines also had individuals of *Septifer* sp., *P. viridis*, *Byssogerdius subsulcatus* (Dunker, 1857) and *Modiolus* sp., along with the oysters *Magellana bilineata* (Röding, 1798) and *Saccostrea cucullata* (Born, 1778) (Table 1).

Ten rocky shore and concrete jetties on the open coast were sampled (Table 1) but *M. strigata* was found only at Bang Saen (Site 1). It was also found in small numbers on the hanging ropes at Si Racha (Site 2). It was not detected at the three sites (Sites 7, 8 and 9) examined further south in Kungkrabaen Bay or in the Mangrove Ecology Learning Center at Sirinart Rajini (Site 17).

**Mytella strigata in aquaculture ponds**

The mussel was abundant in the aquaculture pond at Prachuap Kiri Khan (Site 15) where the salinity was 40 PSU. The mussels were in small clumps ≤ 30 cm in diameter, not as a continuous bottom as occurred in 2018. The population was unimodal; the mean size of 449 individuals measured was 33.5 ± 0.3 mm (SE), with a range of 16 to 58 mm (Figure 3a).

*Mytella strigata* also occurred in clumps several centimetres thick at Samut Sakhon (Site 20) (Figure 4), where the salinity was 30 PSU. There was a significant difference in the shell lengths of *M. strigata* populations in the two ponds sampled (t-test, p < 0.001) (Figure 3b, c). In pond 1 the 125 mussels averaged 26.7 ± 0.4 mm, with range of 16 to 37 mm, but in pond 2 the 127 mussels averaged 55.0 ± 0.7 mm, with a range of 28 to 65 mm.

**Overlap of Mytella strigata and Pern a viridis in the Bangpakong River**

*Mytella strigata* and *P. viridis* both occurred at all three sites in the Bangpakong River. At all three sites *M. strigata* was much more abundant than *P. viridis*, ranging from 2.5:1 at the downstream site at Bird Island (Site 11) to 10.4:1 at the Fisherman’s Hut (Site 12) and 11:1 upstream at the Bangpakong River Bridge (Site 13) (Table 2). The mean shell length of *P. viridis* was significantly greater at all three sites than *M. strigata*. The difference was greatest at Bird Island (37.7 ± 1.1 mm vs. 15.8 ± 0.5 mm) (t-test, p < 0.001).
Figure 3. Size frequency graphs of *Mytella strigata* in three aquaculture ponds in the upper Gulf of Thailand in August 2023; (a) Prachuap Kiri Khan, (b) Samut Sakhon pond 1, (c) Samut Sakhon pond 2.

Figure 4. *Mytella strigata* from the aquaculture pond at Samut Sakon. Photograph by Kitithorn Sanpanich.
Table 2. Comparison of *Mytella strigata* and *Perna viridis* numbers and shell lengths in the Bangpakong River in the upper Gulf of Thailand in August 2023.

<table>
<thead>
<tr>
<th>Location</th>
<th>Bird Island</th>
<th>Fisherman’s hut</th>
<th>Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>11</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Species</td>
<td><em>M. strigata</em></td>
<td><em>P. viridis</em></td>
<td><em>M. strigata</em></td>
</tr>
<tr>
<td>Number</td>
<td>286</td>
<td>113</td>
<td>249</td>
</tr>
<tr>
<td>Mean ± SE (mm)</td>
<td>15.8 ± 0.5</td>
<td>37.7 ± 1.1</td>
<td>39.4 ± 0.6</td>
</tr>
<tr>
<td>Range (mm)</td>
<td>2–41</td>
<td>16–55</td>
<td>6–63</td>
</tr>
</tbody>
</table>

The mean shell lengths of *P. viridis* at the three sites were relatively constant, ranging from 37.7 ± 1.1 mm at Bird Island to 51.0 ± 0.7 mm at the Bangpakong Bridge (Table 2), but the difference between sites was statistically significant (t-test, p < 0.001). In comparison, the mean shell lengths of *M. strigata* were much more variable, varying significantly from 15.8 ± 0.5 mm at Bird Island to 40.1 ± 0.2 mm at the Bangpakong Bridge (t-test, p < 0.001).

**Sale of Mytella strigata in local markets**

A number of stalls at the Samaesan fish market (near Site 3) were selling a range of molluscs, including octopus, squid, cockles, oysters, snails and *P. viridis*, but none were selling *M. strigata*. Similarly, three roadside stalls were visited on the open road near the Bangpakong River bridge. While they had molluscs, including *P. viridis*, they were not selling *M. strigata*.

**Discussion**

The key questions are whether the species is still occurring in the upper Gulf of Thailand in August 2023 region nearly five years after the November 2018 survey by Sanpanich and Wells (2019) and whether its range has subsequently expanded. The distribution of the species in 2023 was essentially the same. The southernmost site on the western side of the gulf was at Prachuap Kiri Khan in both years. Similarly, no *M. strigata* were found south of Si Racha in 2018; in 2023 freshly dead shells with remaining tissue fragments were found inshore of a *P. viridis* mussel farm at Ta Kuan Beach, about 77 km south of Si Racha. As this site was not surveyed in 2018 we do not know whether *M. strigata* was present at that site five years ago. No *M. strigata* were found at sites south of Ta Kuan Beach. It should be noted that the population in the aquaculture pond at Prachuap Kiri Khan was deliberately introduced from Samut Sakon to be a potential food for aquaculture species (Sanpanich and Wells 2019). No populations were detected between the two locations in either survey.

Songkla Lakes, where Wangkulangkul et al. (2022) recently reported *M. strigata* is about 550 km south of our closest survey site at Prachuap Kiri Khan. It is not known whether the Songkla Lake population was introduced from the upper Gulf of Thailand, another Southeast Asian country or from native populations of the species in the eastern Pacific and Caribbean Sea.
However, it is clear that the range of *M. strigata* in the upper Gulf of Thailand remained relatively static over the nearly five years between surveys. This contrasts with the rapid spread of the species in the Philippines (Rice et al. 2016; Mediodia et al. 2017; Vallejo et al. 2017; Fabiosa et al. 2021; Fuertes et al. 2021) and in Southeast Asia, India and Hong Kong (Lim et al. 2018; Sanpanich and Wells 2019; Jayachandran et al. 2019; Huang et al. 2021; Ma et al. 2022; Joyce et al. 2023). It also contrasts with the demise of other species of mussels that have been recorded in other localities, including *Arcuatula senhousia* in the Swan River, Western Australia (McDonald and Wells 2010); *Perna viridis* in Cairns, Queensland (Stafford et al. 2007), *Mytilus galloprovincialis* in South Africa (Robinson et al. 2007) and *Perna perna* in Israel (Galil et al. 2022).

The 2023 survey of 20 sites in the upper Gulf of Thailand demonstrated a considerable habitat specificity for *M. strigata* in the area. The mussel was found at only eight of the sites surveyed: three in the estuary of the Bangpakong River; two in aquaculture ponds and two in *P. viridis* mussel farms. Only one of 10 sites on the open coast had *M. strigata*. The site was at Bang Saen, close to the substantial populations in the Bangpakong River. The report by Wangkulangkul et al. (2022) of *M. strigata* in the Songkla Lakes of the southwestern Gulf of Thailand is consistent with the records of the species in the upper Gulf of Thailand, suggesting further surveys for *M. strigata* in Thailand should concentrate on estuaries, aquaculture ponds and *P. viridis* farms rather than intertidal hard substrates on open coasts.

The absence of *M. strigata* from open coast sites in the upper Gulf of Thailand is consistent with findings in other countries. The mussel is considered to be a brackish water, or estuarine, species (Yuan et al. 2010; Lim et al. 2018; Huang et al. 2021; Jayachandran et al. 2019). Yuan et al. (2010) conducted laboratory experiments that demonstrated both small and large individuals of *M. strigata* (as *M. charruana*) are able to tolerate salinities ranging from 2 to 40 PSU, but the species is typically found in brackish water areas. The salinity in most open areas of the upper Gulf of Thailand is 31–32 PSU (Guo et al. 2021), which may partly explain its absence on open rocky shore coastlines. The broad salinity tolerances reported by Yuan et al. (2010) do not necessarily mean the species will actually establish populations in higher salinity environments. The false mussel *Mytilopsis sallei* (Rccluz, 1849) has a similarly broad range of salinity tolerances in laboratory experiments (Rajagopal and Van Der Velde 2012). The species has long been known since 2001 from the Songkla Lakes region in southwestern Thailand, but has remined primarily in brackish waters in the region (Wangkulangkul and Lheknim 2008; Klangnurak and Wangkulangkul 2021).

There is no information on reproductive seasonality of *M. strigata* in the upper Gulf of Thailand or elsewhere in Southeast Asia. All of the size frequency graphs of *M. strigata* measured during the current survey were
unimodal. This suggests there is one annual spawning, but there were significant differences in mean sizes in adjacent sites in Samut Sakhon and the Bangpakong River, which suggests there may be small scale differences in reproductive seasonality or alternatively in growth rates. Reproductive seasonality and growth rates of *M. strigata* in Southeast Asia need to be examined.

In 2023 *M. strigata* co-occurred with *P. viridis* at the three sites in the Bangpakong River, as it did in the 2018 survey. *Mytella strigata* dominated numerically at all sites in both years, but *P. viridis* were significantly larger than *M. strigata*. Local fishermen have been concerned that *M. strigata* are outcompeting *P. viridis* (Sanpanich and Wells 2019). This concern, and possible other effects of *M. strigata* on other species and marine biodiversity is raised in most other papers from Asia (e.g. Lim et al. 2018; Jayachandran et al. 2019; Fabiosa et al. 2021; Huang et al. 2021; Ravinesh et al. 2023; Joyce et al. 2023). However, there is a paucity of hard data on the actual effects of the mussel. Perhaps the clearest demonstration of effects was that of Fuertes et al. (2021), who conducted interviews with focus groups of local fishermen and concluded *M. strigata* was causing reduced catches of Asian green mussels and oysters. There is an urgent need to undertake quantitative studies on the environmental and economic effects of *M. strigata* in the Asian marine environments in which it has been introduced.

The charru mussel was present in the markets surveyed in November 2018 but not in August 2023. This may have been due to the three month difference in the timing of the surveys, but discussions with the market vendors indicated that *P. viridis* is preferred to *M. strigata* and the charru mussel receives a lower price. Fuertes et al. (2021) found that in the Philippines *M. strigata* outcompeted *P. viridis*, causing slower growth, increased mortality, a lower market price and increased handling costs of separating *M. strigata* from *P. viridis*.

In summary, the spread of the mussel *M. strigata* has been continuing widely in Asia in recent years. In contrast, the population in the upper Gulf of Thailand appears to be relatively stable and has not spread since it was first reported by Sanpanich and Wells (2019). There is an urgent requirement to undertake basic biological research on population parameters such as reproductive periodicity, growth rates and, in particular, the environmental and economics of the widespread invasion of this species.

**Authors’ contribution**

FW: Research conceptualization; sample design and methodology; investigation and data collection; ethical guidelines; data analysis and interpretation; funding provision; roles/writing – original draft; writing – review and editing. TD: Research conceptualization; sample design and methodology; investigation and data collection; ethical guidelines; data analysis and interpretation; writing – review and editing. KS: Research conceptualization; sample design and methodology; investigation and data collection; ethical guidelines; data analysis and interpretation; writing – review and editing. SL: Research conceptualization; sample design and methodology; investigation and data collection; ethical guidelines; data analysis and interpretation; writing – review and editing.
Acknowledgements

We thank Takhon Kakhaikijwatav, Kungkrabaen Bay Royal Development Study Center, Department of Fisheries, Ministry of Agriculture and Co-operatives, Chanthaburi Province, Attawut Kuntavong, Si Racha Fisheries Research Station; Kasetsart University, Chon Buri Province and Komson Hongpadharakiree, Sirinath Rajini Mangrove Ecosystem Learning Center, Prachuap Khiri Khan province for their assistance in the field. This work was undertaken as part of the eDNA for Global Environment Studies (eDGES) program (https://research.curtin.edu.au/scieng/edges/) at Curtin University. We warmly thank BHP, their program manager, Dr Tim Cooper, and the Curtin manager of the eDGES program, Dr Euan Harvey, for their invaluable support. We also acknowledge the careful assistance of the handling editor and reviewers of the manuscript.

Funding declaration

The project was funded by BHP’s Social Investment Framework, “Environment” stream by contributing to “biodiversity conservation, water stewardship and climate change mitigation and adaptation”. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Ethics and permits

There are no ethical requirements for handling of mussels. The research was undertaken under a permit issued by the National Research Council of Thailand.

References


Slack-Smith SM, Brearley A (1987) *Musculista senhousia* (Benson, 1842); a mussel recently introduced into the Swan River estuary, Western Australia. Records of the Western Australian Museum 13: 225–230


Vallejo B Jr., Conejar-Espedido J, Manubag L, Artiaga KCC, Damatac II AM, Imperial ICVJ, Itong 858–870


Wells FE, McDonald JI, Huisman JM (2009) Introduced marine species in Western Australia. *Western Australian Department of Fisheries, Perth Fisheries Occasional Publications* 57: 1–97


**Websites and online databases**


NEMESIS (2023) National Estuarine and Marine Exotic Species Information System. https://invasions.si.edu/nemesis/ (accessed September 2023)