BioInvasions Records (2024) Volume 13, Issue 1: 69–82

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. Wells[1,2], Teerapong Duangdee[3], Kitithorn Sanpanich[4] and Sherralee S. Lukehurst[1]

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

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

Citation: Wells FE, Duangdee T, Sanpanich K, Lukehurst SS (2024) Status of the invasive charru mussel *Mytella strigata* (Hanley, 1843) in the upper Gulf of Thailand five years after it was first surveyed. *BioInvasions Records* 13(1): 69–82, https://doi.org/10.3391/bir.2024.13.1.07

Received: 11 October 2023
Accepted: 2 January 2024
Published: 19 February 2024

Handling editor: Ting Hui Ng
Thematic editor: Amy Fowler

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

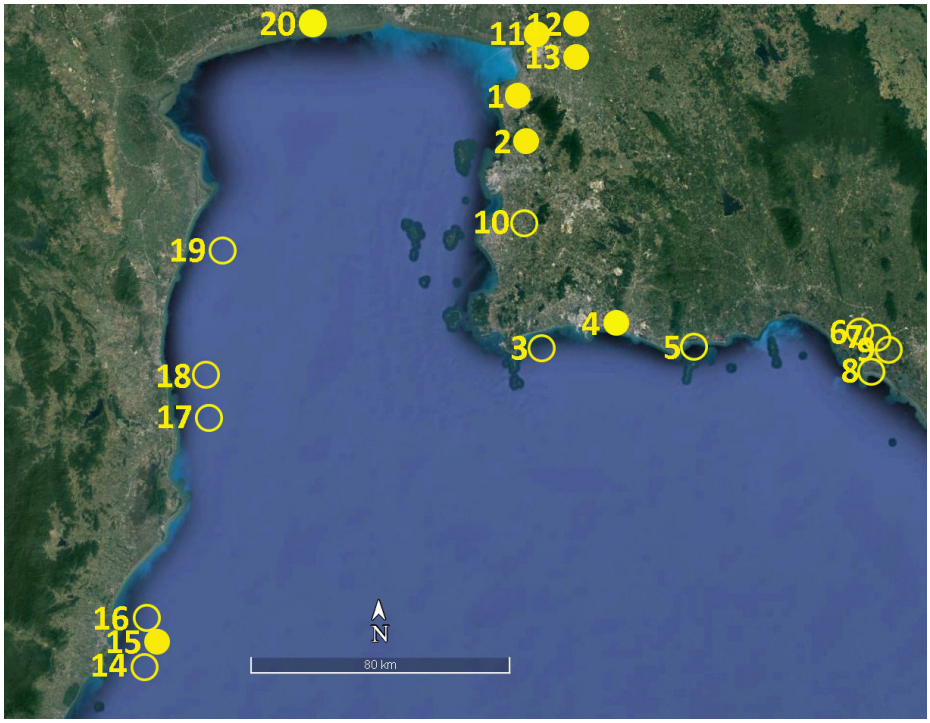

Figure 1. Map of sites sampled for *Mytella strigata* in the upper Gulf of Thailand in August 2023**.** Map prepared by Kitithorn Sanpanich using Google Earth. Closed circles indicate that the species was present, open circles indicate that the species was absent.

(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 the inner 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.

Site no.	Location	Latitude (°N)	Longitude (°E)	Date	Habitat	Mussel species detected 2023	*M. strigata* in 2018
1	Bang Saen Beach	13.300	100.900	1 Aug 2023	Rocky shore on open coast	Patches of *M. strigata* < 10 mm	NS
2	Kasetsart University Fisheries Research Center, Si Racha	13.179	100.921	1 Aug 2023	Hanging ropes	*M. strigata, P. viridis, B. subsulcatus*, *Modiolus* sp., *Septifer* sp.	YES
3	Samaesan	12.599	100.949	2 Aug 2023	Rocky shore on open coast	None	NS
4	Ta Kuan Beach	12.672	101.165	2 Aug 2023	Hanging ropes	*M. strigata, P. viridis* washed up from offshore mussel farm. *B. subsulcatus, Modiolus* sp. live on rocks.	NS
5	Mae Rum Peung Beach	12.611	101.384	2 Aug 2023	Rocky shore on open coast	None	NS
6	Hin Khrong, north of Kungkrabaen Bay	12.608	101.870	3 Aug 2023	Rocky shore on open coast	None	NS
7	Mouth of Kungkrabaen Bay	12.587	101.884	3 Aug 2023	Rocky shore on open coast	None	NS
8	Southern Kungkrabaen Bay	12.581	101.892	3 Aug 2023	Rocky shore and wall in bay	None	NS
9	Kungkrabaen Bay, Sea Farming Demonstration Unit	12.582	101.892	3 Aug 2023	Hanging ropes in bay	None *P. viridis*	NS
10	Pattaya	12.974	100.890	4 Aug 2023	Rocky shore and wall on open coast	*B. subsulcatus, Modiolus* sp., dead *P. viridis*	NS
11	Bangpakong River: Bird Island	13.496	100.982	5 Aug 2023	Hanging rope in river	*M. strigata, P. viridis*	YES
12	Bangpakong River: Fisherman's House	13.503	100.981	5 Aug 2023	Jetty in river	*M. strigata, P. viridis*	YES
13	Bangpakong River: Bangpakong Bridge	13.485	101.003	5 Aug 2023	Jetty in river	*M. strigata, P. viridis*	YES
14	Klongwan Pier	11.736	99.782	6 Aug 2023	Jetty on open coast	None	NS
15	Prachuap Kiri Khan Coastal Aquaculture Research and Development Center, Klongwan	11.750	99.792	6 Aug 2023	Mud bottom on side of aquaculture pond	*M. strigata*	YES
16	Khao Ta Mong Lai Forest Park	11.837	99.830	6 Aug 2023	Rocky shore on open coast	None	NS
17	Sirinath Rajini Mangrove Ecology Learning Center	12.393	99.982	7 Aug 2023	*Rhizophora* mangroves	None	NO
18	Kao Ta Kiep	12.514	99.981	7 Aug 2023	Jetty on open coast	None	NS
19	Institute of Marine Science, Burapha University (Cha Am)	12.872	100.018	8 Aug 2023	Rock wall on open coast	None	NO
20	Marine and Coastal Resources Research and Development Centre (Upper Gulf of Thailand), Samut Sakhon Province.	13.502	100.270	8 Aug 2023	Mud bottom on side of aquaculture pond	*M. strigata*	YES

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).

Figure 2. Mixture of *Mytella strigata* and *Perna viridis* on a rope at Bird Island, upper Gulf of Thailand in August 2023. Photograph by Fred Wells.

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 *M. 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 ± 0.4mm, 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* Perna 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, $p < 0.001$).

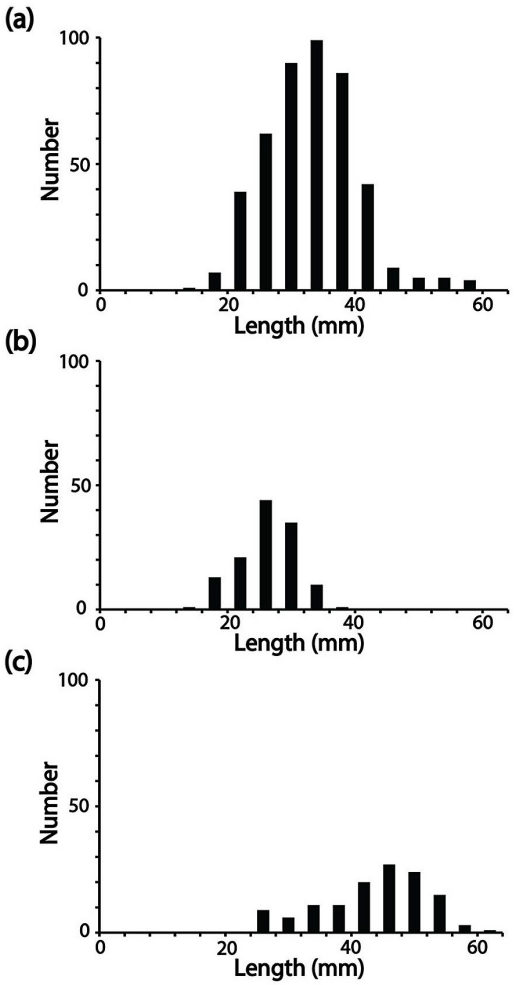

Figure 3. Size frequency graphs of *Mytella strigata* in three aquaculture ponds in the upper Gulf of Thailand in August 2023; (a) Prachuap Kiri Khan, (b) Samut Sakhon pond 1, (c) Samut Sakhon pond 2.

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.

Location	Bird Island		Fisherman's hut		Bridge	
Site	11		12		13	
Species	*M. strigata*	*P. viridis*	*M. strigata*	*P. viridis*	*M. strigata*	*P. viridis*
Number	286	113	249	24	364	32
Mean ± SE (mm)	15.8 ± 0.5	37.7 ± 1.1	39.4 ± 0.6	46.3 ± 1.7	40.1 ± 0.2	51.0 ± 0.7
Range (mm)	2–41	16–55	6–63	29–60	25–53	41–60

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* (Récluz, 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 Kakhaikijtawat, 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 udertaken under a permit issues by the National Research Council of Thailand.

References

Agard J, Kishore R, Bayne B (1992) *Perna viridis* (Linnaeus, 1758): first record of the Indo- Pacific green mussel (Mollusca: Bivalvia) in the Caribbean. *Caribbean Marine Studies* 3: 59–60

Arcella TE, Perry WL, Lodge DM, Federc JL (2014) The role of hybridization in a species invasion and extirpation of resident fauna: Hybrid vigor and breakdown in the rusty crayfish, *Orconectes rusticus*. *Journal of Crustacean Biology* 34: 157–164, https://doi.org/10.1163/1937240X-00002204

Astudillo J-C, Wong JCY, Dumont CP, Bonebrake TC, Leung KMY (2014) Status of six nonnative marine species in the coastal environment of Hong Kong, 30 years after their first record. *BioInvasions Records* 3: 123–137, https://doi.org/10.3391/bir.2014.3.3.01

Astudillo J-C, Bonebrake TC, Leung KMY (2017) The recently introduced bivalve *Xenostrobus securis* has higher thermal and salinity tolerance than the native *Brachidontes variabilis* and established *Mytilopsis sallei*. *Marine Pollution Bulletin* 118: 229–236, https://doi.org/10.1016/j.marpolbul.2017.02.046

Barber BJ, Fajans JS, Baker SM, Baker P (2005) Gametogenesis in the non-native green mussel, *Perna viridis*, and the native scorched mussel, *Brachidontes exustus*, in Tampa Bay, Florida. *Journal of Shellfish Research* 24: 1087–1095, https://doi.org/10.2983/0730-8000(2005)24[1087:GITNGM]2.0.CO;2

Barbieri M, Maltagliati F, di Giuseppe G, Cossu P, Lardicci C, Castelli A (2011) New records of the pygmy mussel *Xenostrobus securis* (Bivalvia: Mytilidae) in brackish-water biotopes of the western Mediterranean provide evidence of its invasive potential. *Marine Biodiversity Records* 4: 1–4, https://doi.org/10.1017/S175526721100042X

Boudreaux ML, Walters LJ (2006) *Mytella charruana* (Bivalvia: Mytilidae): a new, invasive bivalve in Mosquito Lagoon, Florida. *The Nautilus* 120: 34–36

Branch GM, Steffani CN (2004) Can we predict the effects of alien species? A case-study of the invasion of South Africa by *Mytilus galloprovincialis* (Lamarck). *Journal of Experimental Marine Biology and Ecology* 300: 189–215, https://doi.org/10.1016/j.jembe.2003.12.007

Calazans CSH, Walters LJ, Fernandes FC, Ferreira CEL, Hoffman EA (2017) Genetic structure provides insights into the geographic origins and temporal change in the invasive charru mussel (Sururu) in the southeastern United States. *PLoS ONE* 12: e0180619, https://doi.org/10.1371/journal.pone.0180619

Chavanich S, Tan LT, Vallejo B (2010) Report on the Current Status of Marine Non-Indigenous Species in the Western Pacific Region. Chulalongkorn University, Bangkok, 71 pp

Colautti RI, Lau JA (2015) Contemporary evolution during invasion: Evidence for differentiation, natural selection, and local adaptation. *Molecular Ecology* 24: 1999–2017, https://doi.org/10.1111/mec.13162

Crooks JA (2002) Predators of the invasive mussel *Musculista senhousia* (Mollusca: Mytilidae). *Pacific Science* 56: 49–57, https://doi.org/10.1353/psc.2002.0002

Crowe TP, Frid CLJ (eds) (2015) Marine Ecosystems: Human Impacts on Biodiversity, Functioning and Services. Cambridge University Press, Cambridge UK, 397 pp, https://doi.org/10.1017/CBO9781139794763

Dias PJ, Fotedar S, Snow M (2014) Characterisation of mussel (*Mytilus* sp.) populations in Western Australia and evaluation of potential genetic impacts of mussel spat translocation from interstate. *Marine and Freshwater Research* 65: 486–496, https://doi.org/10.1071/MF13179

Dogan A, Önen M, Öztürk B (2007) A new record of the invasive Red Sea mussel *Brachidontes pharaonis* (Fischer P., 1870) (Bivalvia: Mytilidae) from the Turkish coasts. *Aquatic Invasions* 2: 461–463, https://doi.org/10.3391/ai.2007.2.4.20

Fabiosa MP, Abao CAA, Fabiosa NP, Uba KIN (2021) First record of the invasive mussel *Mytella strigata* (Mollusca: Bivalvia: Mytilidae) in Panguil Bay, Southern Philippines. *Journal of Environment and Aquatic Resources* 6: 35–46, https://doi.org/10.48031/msunjear.2021.06.03

Fuertes VNB, de los Reyes RA, Monteclaro HM (2021) The spread of the non-indigenous mussel species *Mytella strigata* (Hanley, 1843) in the Philippines: Ensuing issues and responses of local communities. *Regional Studies in Marine Science* 41: 101576, https://doi.org/10.1016/j.rsma.2020.101576

Galil BS, Mienis HK, Mendelson M, Gayer K, Goren M (2022) Here today, gone tomorrow - the Levantine population of the brown mussel *Perna* obliterated by unprecedented heatwave. *Aquatic Invasions* 17: 174–185, https://doi.org/10.3391/ai.2022.17.2.03

Griffiths CL, Hockey P, Van Erkom Schurink C, LeRoux PJ (1992) Marine invasive aliens on South African shores: Implications for community structure and trophic functioning. *South African Journal of Marine Science* 12: 713–722, https://doi.org/10.2989/02577619209504736

Guo J, Qu D, Zhang Z, Sangmanee C, Chanthasiri N, Guo B (2021) Thermohaline conditions and circulation in the Gulf of Thailand during the northeast monsoon. *Continental Shelf Research* 225: 104487, https://doi.org/10.1016/j.csr.2021.104487

Hallegraeff GM, Steffensen DA, Wetherbee R (1988) Three estuarine Australian dinoflagellates that can produce paralytic shellfish toxins. *Journal of Plankton Research* 10: 533–541, https://doi.org/10.1093/plankt/10.3.533

Huang Y-C, Li Z-K, Chen W-L, Chan C-C, Hsu H-Y, Lin Y-T, Huang Y-S, Han Y-S (2021) First record of the invasive biofouling mussel *Mytella strigata* (Hanley, 1843) (Bivalvia: Mytilidae) from clam ponds in Taiwan. *BioInvasions Records* 10: 304–312, https://doi.org/10.3391/bir.2021.10.2.08

Jayachandran PR, Aneesh BP, Oliver PG, Philomena J, Jima M, Harikrishnan K, Nandan SB (2019) First record of the alien invasive biofouling mussel *Mytella strigata* (Hanley, 1843) (Mollusca: Mytilidae) from Indian waters. *BioInvasions Records* 8: 828–837, https://doi.org/10.3391/bir.2019.8.4.11

Joyce PWS, Lee SY, Falkenberg LJ (2023) First record of the alien invasive mussel *Mytella strigata* (Hanley, 1843) in Hong Kong. *BioInvasions Records* 12: 385–391, https://doi.org/10.3391/bir.2023.12.2.03

Katsanevakis S, Wallentinus I, Zenetos A, Leppäkoski E, Çinar ME, Oztürk B, Grabowski M, Golani D, Cardoso AC (2014) Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. *Aquatic Invasions* 9: 391–423, https://doi.org/10.3391/ai.2014.9.4.01

Klangnurak W, Wangkulangkul K (2021) Mitochondrial DNA Analysis Suggests Invasion of Thailand Coast by a Single Species of Dreissenidae, *Mytilopsis sallei. Journal of Fisheries and Environment* 45: 64–76

Lim JY, Tay TS, Lim CS, Lee SSC, Teo SL-M, Tan KS (2018) *Mytella strigata* (Bivalvia: Mytilidae): an alien mussel recently introduced to Singapore and spreading rapidly. *Molluscan Research* 38: 170–186, https://doi.org/10.1080/13235818.2018.1423858

Lodeiros C, Hernández-Reyes D, Salazar JM, Rey-Méndez M, González-Henríquez N (2021) First report of the mussel *Mytella strigata* (Hanley, 1843) in the Venezuelan Caribbean from an invasion in a shrimp farm. *Latin American Journal of Aquatic Research* 49: 531–537, https://doi.org/10.3856/vol49-issue3-fulltext-2626

Lowe S, Browne M, Boudjelas S, De Poorter M (2004) 100 of the World's Worst Invasive Alien Species A selection from the Global Invasive Species Database. The Invasive Species Specialist Group (ISSG) World Conservation Union (IUCN), 12 pp

Ma P-Z, Li H-M, Liu Y-M, Li C, Zhang Z, Wang H-Y (2022) First confirmed occurrence of the invasive mussel *Mytella strigata* (Hanley, 1843) in Guangdong and Hainan, China, and its rapid spread in Indo-West Pacific regions. *BioInvasions Records* 11: 947–963, https://doi.org/10.3391/bir.2022.11.4.13

McDonald JI, Wells FE (2010) The apparent demise of the Asian date mussel *Musculista senhousia* in Western Australia: or using acts of god as an eradication tool. *Biological Invasions* 12: 715–719, https://doi.org/10.1007/s10530-009-9478-4

McDonald JI, Wellington CM, Coupland GT, Pedersen D, Kitchen B, Bridgwood SD, Hewitt M, Duggan R, Abdo DA (2020) A united front against marine invaders: Developing a cost- effective marine biosecurity surveillance partnership between government and industry. *Journal of Applied Ecology* 57: 77–84, https://doi.org/10.1111/1365-2664.13557

Mediodia DP, De Leon SMS, Anasco NC, Baylon CC (2017) Shell morphology and anatomy of the Philippine charru mussel *Mytella charruana* (d'Orbigny, 1842). *Asian Fisheries Science* 30: 185–194, https://doi.org/10.33997/j.afs.2017.30.3.004

Popovic I, Matias AMA, Bierne N, Riginos C (2020) Twin introductions by independent invader mussel lineages are both associated with recent admixture with a native congener in Australia. *Evolutionary Applications* 13: 515–532, https://doi.org/10.1111/eva.12857

Rajagopal S, Van Der Velde S (2012) Invasive species implications for industrial cooling water systems. In: Rajagopal S, Jenner HA, Venugopalan VP (eds), Operational and environmental consequences of large industrial cooling water systems. Springer, New York, U.S.A., pp 127–162, https://doi.org/10.1007/978-1-4614-1698-2_7

Ravinesh R, Laju RL, Edward JKP, Biju Kumar A (2023) Invasion of alien mussel *Mytella strigata* (Bivalvia: Mytilidae) in the Gulf of Mannar, India and possible threats to the native biodiversity. *Journal of Aquatic Biology & Fisheries* 11: 28–34

Rice MA, Rawson PD, Salinas AD, Rosario WR (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, https://doi.org/10.2983/035.035.0415

Rilov G, Benayahu Y, Gasith A (2004) Prolonged lag in population outbreak of an invasive mussel: a shifting-habitat model. *Biological Invasions* 6: 347–364, https://doi.org/10.1023/B:BINV.0000034614.07427.96

Rius M, Turon X, Bernardi G, Volckaert FA, Viard F (2015) Marine invasion genetics: From spatio-temporal patterns to evolutionary outcomes. *Biological Invasions* 17: 869–885, https://doi.org/10.1007/s10530-014-0792-0

Robinson TB, Griffiths CL, Branch GM, Govender A (2007) The invasion and subsequent die- off of *Mytilus galloprovincialis* in Langebaan Lagoon, South Africa: Effects on natural communities. *Marine Biology* 152: 225–232, https://doi.org/10.1007/s00227-007-0697-x

Salimi PA, Creed JC, Esch MM, Fenner D, Jaafar Z, Levesque JC, Montgomery AD, Salimi MA, Edward JKP, Raj KD, Sweet M (2021) A review of the diversity and impact of invasive non-native species in tropical marine ecosystems. *Marine Biodiversity Records* 14: 11, https://doi.org/10.1186/s41200-021-00206-8

Sanpanich K (2011) Marine bivalves occurring on the east coast of the Gulf of Thailand. *ScienceAsia* 37: 195–204, https://doi.org/10.2306/scienceasia1513-1874.2011.37.195

Sanpanich K, Wells FE (2019) *Mytella strigata* (Hanley, 1843) emerging as an invasive marine threat in Southeast Asia. *BioInvasions Records* 8: 343–356, https://doi.org/10.3391/bir.2019.8.2.16

Shine R (2010) The ecological impact of invasive cane toads (*Bufo marinus*) in Australia. *The Quarterly Review of Biology* 85: 253–291, https://doi.org/10.1086/655116

Siddall SE (1980) A clarification of the genus *Perna* (Mytilidae). *Bulletin of Marine Science* 30: 858–870

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

Spinuzzi S, Schneider KR, Walters LJ, Yuan WS, Hoffman EA (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, https://doi.org/10.1017/S1755267213000316

Stafford H, Willan RC, Neil KM (2007) The invasive Asian green mussel, *Perna viridis* (Linnaeus, 1758) (Bivalvia: Mytilidae), breeds in Trinity Inlet, tropical northern Australia. *Molluscan Research* 27: 105–109, https://doi.org/10.11646/mr.27.2.4

Vallejo B Jr., Conejar-Espedido J, Manubag L, Artiaga KCC, Damatac II AM, Imperial ICVJ, Itong TAB, Fontanilla IK, Cao EP (2017) First record of the Charru mussel *Mytella charruana* d'Orbigny, 1846 (Bivalvia: Mytilidae) from Manila Bay, Luzon, Philippines. *BioInvasions Records* 6: 49–55, https://doi.org/10.3391/bir.2017.6.1.08

Wangkulangkul K, Lheknim V (2008) The occurrence of an invasive alien mussel *Mytilopsis adamsi* Morrison, 1946 (Bivalvia: Dreissenidae) in estuaries and lagoons of the lower south of the Gulf of Thailand with comments on their establishment. *Aquatic Invasions* 3: 325–330, https://doi.org/10.3391/ai.2008.3.3.7

Wangkulangkul K, Hayeewachi L, Rodcharoen E (2022) Changes in benthic macro-invertebrate assemblages in an estuary in southern Thailand after invasion by non-native bivalves *Mytilopsis sallei* and *Mytella strigata*. *Plankton & Benthos Research* 17: 137–146, https://doi.org/10.3800/pbr.17.137

Wells FE (2017) If the Asian green mussel, *Perna viridis* (Linnaeus, 1758), poses the greatest invasive marine species threat to Australia, why has it not invaded? *Molluscan Research* 37: 167–174, https://doi.org/10.1080/13235818.2017.1322676

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

Willan RC (1985) Successful establishment of the Asian Mussel *Musculista senhousia* (Benson in Cantor, 1842) in New Zealand. *Records of the Auckland Institute and Museum* 22: 85–96

Yu Y, Gao Q, Liu M, Li J, Wang S, Zhang J (2023) Report on the invasive American brackish- water mussel *Mytella strigata* (Hanley, 1843) (Mollusca: Mytilidae) in Beibu Gulf. *BioInvasions Records* 12: 196–207, https://doi.org/10.3391/bir.2023.12.1.16

Yuan W, Walters LJ, Schneider KR, Hoffman EA (2010) Exploring the survival threshold: a study of salinity tolerance of the nonnative mussel *Mytella charruana*. *Journal of Shellfish Research* 29: 415–422, https://doi.org/10.2983/035.029.0218

Websites and online databases

Heersink D, Paini D, Caley P, Barry Simon (2014) Asian Green Mussel: Estimation of approach rate and probability of invasion via biofouling. CSIRO: EP172373. http://hdl.handle.net/102.100.100/94679?index=1 (accessed 9 September 2023)

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

WoRMS (2023) World Register of Marine Species. https://marinespecies.org/ (accessed September 2023)