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**Rapid Communication****Northern range expansion of the Asian mussel *Arcuatula senhousia* (Benson, 1842) along the French Atlantic coasts**

Cécile Massé<sup>1,\*</sup>, Jérôme Jourde<sup>2</sup>, Denis Fichet<sup>2</sup>, Pierre-Guy Sauriau<sup>2</sup>, Manon Dartois<sup>2</sup>, François Ghillebaert<sup>3</sup> and Chloé Dancie<sup>4</sup>

<sup>1</sup>UMS 2006 Patrimoine Naturel (PATRINAT), OFB, CNRS, MNHN, CP41, 36 rue Geoffroy Saint-Hilaire 75005 Paris, France

<sup>2</sup>UMR 7266 LIENSs CNRS, La Rochelle Université, 2 rue Olympe de Gouges, 17000 La Rochelle, France

<sup>3</sup>ECOTOX, 11 rue Principale, 62380 Affringues, France

<sup>4</sup>Cellule de Suivi du Littoral Normand (CSLN), 53 rue de Prony, 76600 Le Havre, France

\*Corresponding author

Author e-mails: [cecile.masse@mnhn.fr](mailto:cecile.masse@mnhn.fr)

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**OPEN ACCESS****Abstract**

The Asian mussel *Arcuatula senhousia* is known as a successful invader into coastal and estuarine environments worldwide. We here report its Northward expansion along the French Atlantic coast evidenced by new records from the commercial ports of La Rochelle (Bay of Biscay) and Dunkirk (North Sea), both in 2018, following sampling of benthic macroinvertebrates. To date, the Asian mussel has only been observed along the French coast from the Mediterranean Sea and the Southern part of the Bay of Biscay. Its presence in these new locations, which are important for international maritime transport, is most likely related to ship ballast water and/or sediment as vector of introduction. These new insights suggest that this species has not yet finished its expansion process, which could be at the origin of irreversible impacts on ecosystem structure, functioning and services.

**Key words:** non-indigenous, maritime traffic, harbour, France

**Introduction**

The Asian mussel *Arcuatula senhousia* (Benson, 1842) is a small mytilid (Figure 1), with a maximum size of 32 mm, a short lifespan (< 2 years) and high growth rate (Crooks 1996). This semi-buried suspension feeder lives in intertidal and subtidal soft sediments of bays, estuaries and lagoons and is known as a successful invasive species (Crooks 1998; Reusch and Williams 1998; Como et al. 2018). The native area of *A. senhousia* ranges from Siberia to Singapore (Chuang 1961), but it has been introduced in numerous localities worldwide over many decades such as in New-Zealand and Australia (Willan 1985, 1987), the USA (Crooks 1996, 1998; Wasson et al. 2001), India (Kutty et al. 2016) and Africa (Lourenço et al. 2018). Since 1989, it has been regularly reported from European coasts (Figure 2A): in the Mediterranean Sea (Hoenselaar and Hoenselaar 1989; Lazzari and Rinaldi 1994; Mistri et al. 2000; Mistri 2002; Mastrototaro et al. 2003; Zenetos et al. 2003; Doğan et al. 2014; Como et al. 2016; Scirocco and Urbano 2018);

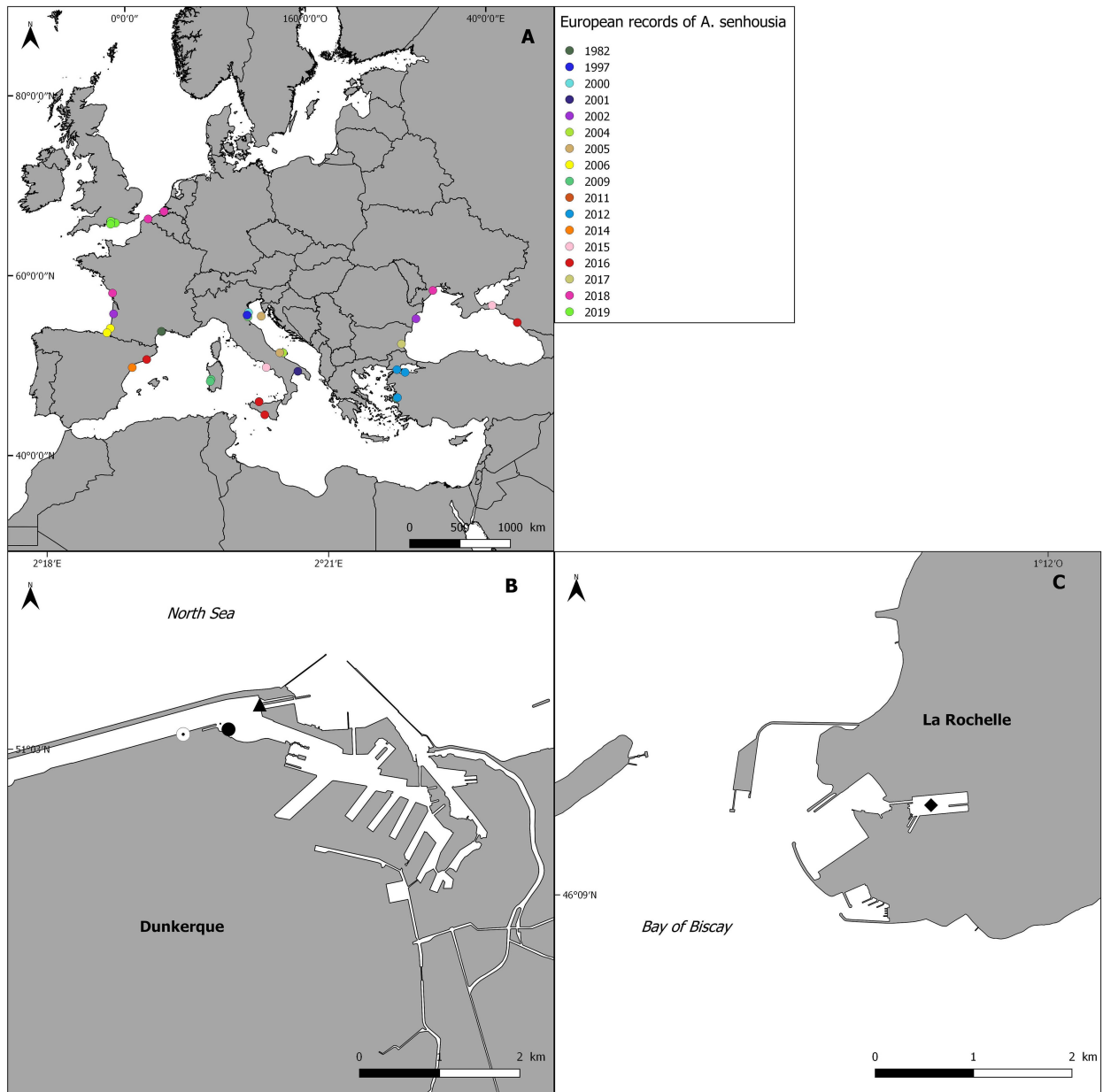


**Figure 1.** *Arcuatula senhousia* specimens (A) from Dunkirk (© Chloé DANCIE), and (B) from Port Atlantique La Rochelle (© Pierre-Guy SAURIAU).

in the Black Sea (Kovalev et al. 2017; Chartosia et al. 2018; Zhulidov et al. 2021); in the Atlantic Ocean in the South of the Bay of Biscay (Bachelet et al. 2009); in UK in the Solent and particularly from Southampton Water estuary since 2007 (Barfield et al. 2018; Holman et al. 2019; Worsfold et al. 2020; Watson et al. 2021); and in the Netherlands (Faasse 2018).

Previous to this study in France, live specimens were observed at the beginning of the 1970s in oyster-spat batches imported from Japan for seafarming along the French Atlantic coasts, but no live specimens were recorded in the environment at that time (Gruet et al. 1976). Live specimens were reported for the first time during the '80s, in Mediterranean lagoons (Hoenselaar and Hoenselaar 1989; Clanzig 1989). Then, Charles (2007) reported the occurrence of large numbers of dead shells in Arcachon Bay, in southwest France, but the species had likely been already present there since 2002 (Bachelet et al. 2009). New records were also reported in the southern Bay of Biscay from the Bidassoa estuary and Hossegor lake by the end of 2006 (Bachelet et al. 2009). Depending on location, the introduction of *A. senhousia* has been attributed either to maritime traffic (e.g., Doğan et al. 2014) or to the activity of marine culture (e.g. Bachelet et al. 2009; Florio et al. 2008).

This non-indigenous species may be responsible for drastic modifications of structure and functioning of benthic communities (Creese et al. 1997; Reusch and Williams 1998), therefore strengthening the need for signalling any new records of the species, namely its expansion, as suggested by Bernard et al. (2020). We reported here new French records of *A. senhousia* from the commercial ports of La Rochelle (Bay of Biscay) and in Dunkirk (North



**Figure 2.** A: Locations of first records of *Arcuatula senhousia* on the different European marine regions by reporting year. Source of records: Bachelet et al. 2009; Chartosia et al. 2018; Como et al. 2016; Crocetta et al. 2015; Doğan et al. 2014; Faasse 2018; Florio et al. 2008; Hoenselaar and Hoenselaar 1989; Kovalev et al. 2017; Lazzari and Rinaldi 1994; Lourenço et al. 2018; Mavrič et al. 2010; Mastrototaro et al. 2003; Micu 2004; Mistri 2002; Mistri et al. 2000; Öztürk et al. 2017; López-Soriano and Quiñonero-Salgado 2014; Ulman et al. 2017; Watson et al. 2021 and references therein; Zhulidov et al. 2021. B: Dunkirk harbour. White dotted circle: Sea Basin Intake station; Black circle: Sea Basin Outfall station; Black triangle: single dead specimen found. C: Port Atlantique La Rochelle. Black diamond: tidal lock basin station with dead and live specimens. For details see Supplementary material Table S1 and Table 1.

Sea) during three different surveys of benthic macrofauna communities (Figure 2B, C). These new records suggest that expansion and/or new introduction events of this species continue and that the invasion process is underway.

### Materials and methods

Specimens from Port Atlantique La Rochelle were collected in 2018 by students enrolled in courses from La Rochelle University from the N/O

**Table 1.** Records of *Arcuatula senhousia* in Port Atlantique La Rochelle (Bay of Biscay) and Dunkirk (North Sea). Lat.: Latitude; Long.: Longitude; Ab: Abundance (individuals per m<sup>2</sup>).

Location	Station	Date	Lat.	Long.	Habitat	Temperature (°C)	Salinity (‰)	Mean Ab. (ind.m <sup>-2</sup> ± SD)
Dunkirk	Sea basin cooling water outfall	March 2018	51.05222	2.33222	Subtidal sandy-mud	8.6	28.8	7 ± 6
		October 2018	51.05223	2.33205	Subtidal sandy-mud	No data	No data	23 ± 11
	Sea basin intake	March 2018	51.05167	2.32417	Subtidal sandy-mud	7.8	28.8	7 ± 6
		October 2018	51.05175	2.32367	Subtidal sandy-mud	No data	No data	33 ± 32
La Rochelle	Tidal lock basin	September 2018	46.15820	-1.21540	Subtidal mud	No data	No data	3 ± 5
		September 2019	46.15820	-1.21540	Subtidal mud	19.8	34.9	97 ± 15

l'Estran, and again in 2019 during the Marine Strategy Framework Directive (MSFD) monitoring of non-indigenous species from the N/O l'Astérie. Sampled stations were located within the tidal lock basin of the harbour. Specimens from Dunkirk port were collected in two stations in the sea basin during a general environmental monitoring for the DK6 (Dunkerque) CCGT Gas Power Plant France in March and October 2018. At all locations, sediment was sampled using a Van Veen grab (0.1 m<sup>2</sup>) and gently sieved through a 1 mm mesh sieve. The remaining fraction was fixed in 4% formalin. Samples were washed in the laboratory to remove formalin, and macrofauna was sorted and preserved in 70% ethanol. The whole benthic faunal community, including *A. senhousia*, was then identified and counted. Temperature and salinity were measured with a multiparameter probe HANNA HI 9828 during sampling. Habitat characteristics, where specimens were recorded, were determined visually.

Species identification: Specimens of *Arcuatula senhousia* were identified following previous descriptions (Slack-Smith and Brearley 1987; Hoenselaar and Hoenselaar 1989; Faasse 2018). Key traits are a brown to greenish periostracum, radiating reddish lines on the posterior part, small internal teeth on the dorsal edge posteriorly to the ligament, and fragile shell with a series of small ribs anterior to the umbones. Some specimens can be more whitish (Figure 1B; Lourenço et al. 2018). *Arcuatula senhousia* cannot be confused with other Mytilidae species from north-eastern Europe (see Tebble 1966).

## Results

In the port of Dunkirk, 4 individuals (7 ± 6 ind.m<sup>-2</sup>) were collected at each station in March 2018. In October 2018, 7 and 10 individuals (23 ± 11 and 33 ± 32 ind.m<sup>-2</sup>) were collected in the outfall and intake sea basin, respectively (Table 1). In March 2018, the lengths of live specimens ranged from 2–8 mm and in October 2018, the lengths of live specimens ranged from 30–32 mm. They were sampled in a muddy sediment characterised by a faunal community dominated by bivalves, particularly the non-indigenous clam *Ruditapes philippinarum* (respectively in the sea basin outfall and intake 33 ± 35 ind.m<sup>-2</sup> and 153 ± 215 ind.m<sup>-2</sup> in March 2018, and 1363 ± 270 ind.m<sup>-2</sup> and 357 ± 81 ind.m<sup>-2</sup> in October 2018).

In the tidal lock basin of the Port Atlantique La Rochelle, 1 live individual (mean  $3 \pm 5$  ind.m<sup>-2</sup>) was sampled in 2018 and 29 individuals (mean:  $97 \pm 15$  ind.m<sup>-2</sup>) in 2019. The lengths of live specimens from 2018 ranged from 8–9 mm, but one dead specimen 14 mm long was also collected (Figure 1B). The sediment from these locations was muddy, and the community was mainly composed of the native bivalves *Nucula nitidosa* and *Varicorbula gibba* (respectively  $1160 \pm 676$  and  $1067 \pm 431$  ind.m<sup>-2</sup>).

## Discussion

*Arcuatula senhousia* has already demonstrated its ability to invade and impact coastal ecosystems. According to the marine non-indigenous species impacts classification of Katsanevakis et al. (2014), *A. senhousia* was classified as an alien species with a high reported impact on ecosystem services or biodiversity. As summarized in Watson et al. (2021), at high densities, the species modifies benthic habitats by forming dense mats of mussels, as observed seasonally in both its native area in Japan (Takenaka et al. 2018) and in invaded ecosystems in California (Crooks 1998). These habitat modifications have consequences on communities (Crooks 1998) and ecosystem functioning such as food webs (Como et al. 2016; Watson et al. 2021) and nutrient cycling (Takenaka et al. 2018; Bernard et al. 2020).

Carboneras et al. (2018) determined that *A. senhousia* should be prioritised for risk assessment and that this species should be added to the list of Invasive Alien Species (IAS) of Union concern (EU regulation 1143/2014) by 2020. In their study, *A. senhousia* was identified as having a “major” impact (according the EICAT classification, Hawkins et al. 2015), due to its scattered distribution (Carboneras et al. 2018). Since the study of Carboneras et al. (2018), the European distribution of *A. senhousia* has increased from scattered to widespread. It was thus excluded from the updated European horizon scanning promoted by Tsiamis et al. (2020).

The first recent observations of the Asian mussel in neighbouring countries such as southern UK (Barfield et al. 2018; Watson et al. 2021) and the Netherlands (Faasse 2018) suggest a step-by-step northward expansion of the species. Bachelet et al. (2009) predicted an expansion of its distribution in North-Western Europe, but through secondary dispersion. Our new French records seem to be in accordance with these expectations. It could be explained by the planktonic larval stage which gives *A. senhousia* a dispersion capacity estimated at 116 Km (Shanks 2009). However, the presence of the species in semi-enclosed harbour basins suggests a new introduction phenomenon. For Port Atlantique La Rochelle, this is very likely a secondary introduction because ships that enter this tidal lock basin only come from local European or Mediterranean waters (Port Atlantique La Rochelle, *pers. comm.*). Until now, French introductions of *A. senhousia* were thought to be associated with oyster transfers (Hoenselaar and

Hoenselaar 1989; Bachelet et al. 2009) but during benthic community monitoring (Jourde, Sauriau, Aubert, *pers. comm.*), the species has hitherto never been encountered in sediments surrounding oyster farms around La Rochelle and Marennes-Oléron Bay that belong to major shellfish farming areas on the French Atlantic coasts (Gouilletquer and Héral 1997), neither in the marina and in the fishing port. Thus, our observations in the semi-enclosed parts of these two harbours are undoubtedly linked to maritime transport. Absence of the species in surrounding areas where the preferential habitat of *A. senhousia* is found (particularly seagrass habitat) does not support the hypothesis of larval dispersion from an invaded site. Adult specimens live in sediments, and larval stages are planktonic. Thus, ballast waters and sediments are the most likely vectors of these introductions. This hypothesis is supported by the detection of *A. senhousia* DNA in ballast water of a boat coming from the Mediterranean Sea (Slijkerman et al. 2017). The International Convention for the control and management of ships' ballast water and sediment (International Maritime Organization) entered into force in 2017. Since then, ships cannot release untreated ballast water in harbours. Assuming that this species has been introduced through ballast waters in these harbour areas, the introduction certainly took place before 2017.

This species tolerates both subtidal and intertidal environments, up to high tidal levels as in the Arcachon Bay (Bachelet et al. 2009). In its native area, *A. senhousia* is mostly found in estuaries, buried in intertidal and subtidal sediments but also sometimes on hard substrates (Morton 1974; Minchin et al. 2016). The first French historical records, until now, were from lagoons or semi-enclosed bays with freshwater inputs (Hoenselaar and Hoenselaar 1989; Bachelet et al. 2009). Hosozawa et al. (2020) found an optimal salinity range of 9.2 to 17.3 for the species in ecosystems of the Sea of Japan. However, *A. senhousia* can tolerate higher salinities (*e.g.* Bachelet et al. 2009; Watson et al. 2021). Here, specimens were encountered in ecosystems with salinities ranging from 20.7 to 34.8 in Dunkirk port and up to 34.9 in the La Rochelle tidal lock basin. High salinities do not seem to prevent the establishment of the species in this latter location because specimens have been observed there since 2018. Both in La Rochelle and Dunkirk, specimens were found in communities dominated by bivalves, as observed by Watson et al. (2021) and particularly in Dunkirk by the non-indigenous clam *Ruditapes philippinarum*. This is in accordance with the positive correlation between abundances of *A. senhousia* and *R. philippinarum* measured in Sacca di Goro in Italy (Munari 2008).

Our records, which are characterised by relatively high densities (up to 97 ind.m<sup>-2</sup>) of *A. senhousia* in a subtidal marine environment and artificial harbour habitats associated with introductions linked to maritime transport, revealed the high capacity of introduction and establishment of the species. Close to these two introduction sites are ecosystems with the preferred

habitat of the Asian mussel (i.e., large intertidal areas with estuarine environmental characteristics and/or *Zostera noltei* Hornemann, 1832 meadows) (Bachelet et al. 2009; Bernard et al. 2020; Watson et al. 2021). As highlighted by Bernard et al. (2020), these surrounding areas must be monitored for possible further spread of the species.

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## Authors' contributions

CM, CD and JJ designed the study, CM, JJ, DF, MD, FG and CD performed the samplings, CM, CD and PGS analysed the results and CM, JJ, CD and PGS wrote the manuscript; all authors reviewed the manuscript.

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### Supplementary material

The following supplementary material is available for this article:

**Table S1.** Locations of first records of *Arcuatula senhousia* on the different European marine regions.

This material is available as part of online article from:

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