THEORA LUBRICA GOULD, 1861 (BIVALVIA: SEMELIDAE), NEW TO THE UK, WITH NOTES ON ASSOCIATED NON-NATIVE SPECIES, AND AN EARLIER DATE OF INTRODUCTION FOR *ARCUATULA SENHOUSIA* (BIVALVIA: MYTILIDAE) TO THE UK

TIM M. WORSFOLD, NICOLA PENNISI & CHRISTOPHER W. ASHELBY

APEM Ltd., Diamond Centre, Works Road, Letchworth Garden City, SG6 1LW, U.K.

Abstract *The non-native bivalve* Theora lubrica *was recorded for the first time for the U.K. in April 2018, from Lake Lothing (Oulton Broad), Lowestoft, Suffolk. This represents the most northerly European record to date for the species. Several other non-native or cryptogenic species were recorded from the same location; in particular, the most northerly European locality of the tubeworm* Hydroides ezoensis *was confirmed.* Theora lubrica *has also been found in the vicinity of Southampton Water and the earliest known U.K. records (May 2011) of the non-native mussel* Arcuatula senhousia*, from the same area, are documented here.*

Key words *Non-native species, window shell, Asian semele, Asian date mussel*

INTRODUCTION

Marine non-native species (NNS) are widespread in European waters, particularly near ports. They are often noted as of environmental concern and standard lists have been produced for the U.K. (Eno *et al.*, 1997; Minchin *et al.*, 2013) and other parts of northern Europe (Reise *et al.*, 1999; Goulletquer *et al.*, 2002; Wolff, 2005; Gollasch & Nehring, 2006; Minchin, 2007; Buschbaum *et al.*, 2012; Katsanevakis *et al.*, 2013). Several databases have also been produced to review NNS regionally and globally whilst new national and regional records are regularly published. Such resources generally include discussion of species' potential impacts and ability to spread and alert lists have been produced for species based on 'horizon scanning' exercises (e.g. Roy *et al.*, 2014).

The semelid, *Theora* (*Endopleura*) *lubrica* Gould, 1861, sometimes known as the Asian semele, is native to north-east Asia (north-west Pacific), from northern Japan and the Russian far east (Lutaenko, 1999; 2006) to Korea (Lutaenko, 2006) and the Yellow Sea, China (Xu, 2008); records from further south may be due to confusion with related species. It was first recorded as a non-native in Port Phillip Bay, Victoria, in 1958 (Macpherson, 1966; Boyd, 1999) and gradually spread throughout southern Australia (Parry *et al.*, 1997) and New Zealand (Climo, 1976; Inglis *et al.*, 2006). Subsequently, the species was also introduced to the Pacific coast of North America (Seapy, 1974). The first European records were from the Livorno, Italy in 2001 (Belena *et al.*, 2002) with a later Mediterranean record made from Israel in 2006 (Bogi & Galil, 2007). The first record from the Atlantic was on the Basque coast, south-eastern Bay of Biscay, where it was found in large numbers in 2010 (Adarraga & Martínez, 2011). It was later recognized in material from the south-western delta region of the Netherlands that had been collected at several locations between 2003 and 2018 (Faasse *et al.*, 2019). Its habitat preferences are for shallow subtidal muddy sediments, typically with a silt/clay content between about 20% and 70% (Ellis *et al.*, 2006). The records detailed in the present paper were mentioned by Faasse *et al.* (2019) and by Taylor (2020) through reference to an unpublished report. *T. lubrica* has since also been recorded from Edinburgh (Notton, 2020). It is tolerant of variable salinity and eutrophication (Hong *et al.*, 1994; Lutaenko, 2006). In its native range, it is found at depths between 1 and 28m, shallowest in the northern parts of its range (Lutaenko, 2006). The animals are deposit feeders, which ingest benthic microalgae (Imabayashi, 1986; Yokoyama & Ishihi, 2003). They may spawn continuously throughout the year (Imabayashi, 1986) and can dominate an area within a short time (Boyd, 1999). The species is tolerant of polluted and disturbed environments (Hayward, 1997; Saito, 2006), although sensitive to very low

Contact author : t.worsfold@apemltd.co.uk

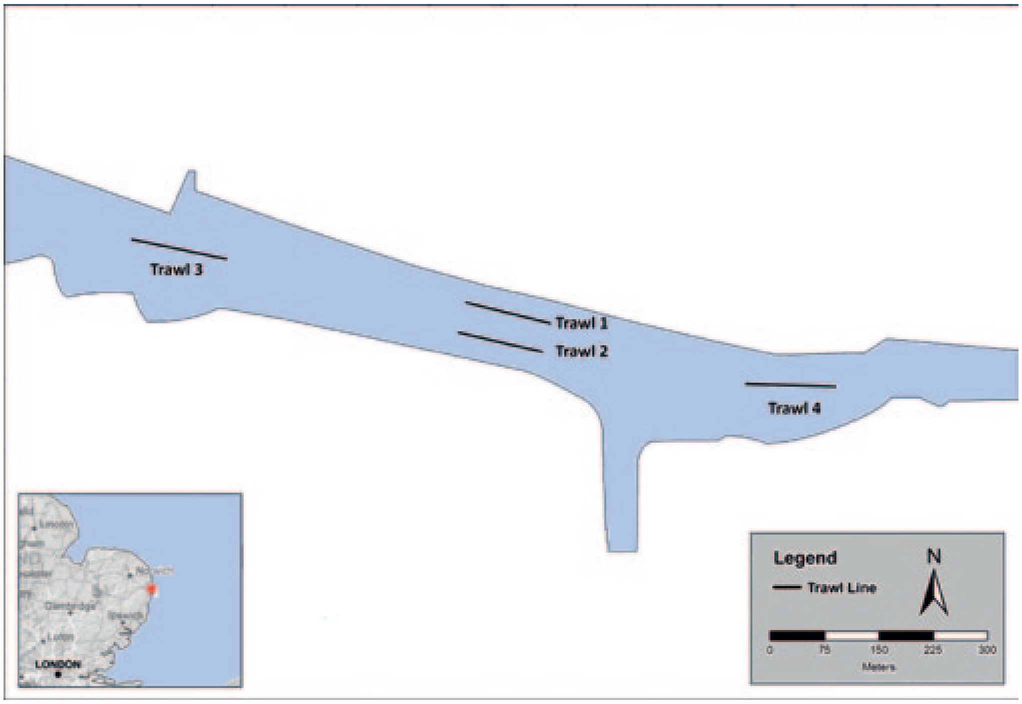

Figure 1 Map of Lake Lothing showing locations of the trawl samples. *Theora lubrica* Gould 1861 was found in Trawl 1 and Trawl 2.

dissolved oxygen levels (Imabayashi, 1986) and to wind-wave disturbance (Ellis *et al*., 2006). It may also alter habitats by liberating nitrogenous compounds from sediments (Yamada & Kayama, 1987).

Lake Lothing (Fig. 1) is the eastern (seaward) extension of Oulton Broad, on the coast of Suffolk, England. It is a tidal inlet (estuary) that extends approximately 3km from the microtidal brackish Oulton broad, which is connected to the River Waveney, to the east; the inlet joins the North Sea at the Port of Lowestoft. It is narrow (about 200m across in most parts), euryhaline and heavily altered by foreshore construction and dredging activity, with disturbed muddy habitats across most of its area.

There have been previous surveys of the inlet that have focussed on sessile non-native species (Bishop *et al*. 2015; Wood *et al*. 2016). They recorded the tubeworm *Hydroides ezoensis* Okuda, 1934, the barnacle *Austrominius modestus* (Darwin, 1854), the skeleton shrimp, *Caprella mutica* Schurin, 1935, the bryozoans *Tricellaria inopinata* d'Hondt & Occhipinti-Ambrogi, 1985, *Bugula neritina* (Linnaeus, 1758), *Bugulina simplex* (Hincks, 1886) and *Bugulina stolonifera* (Ryland, 1960), the ascidians *Styela clava* Herdman, 1881, *Corella eumyota* Traustedt, 1882, *Botrylloides violaceus* Oka, 1927 and *Aplidium* cf . *glabrum* (Verrill, 1871), and wakame (*Undaria pinnatifida* (Harvey) Suringar, 1873). Nearby estuaries in the greater Thames region are known to harbour many other non-native species (e.g. Ashelby, 2005; Bishop *et al*., 2015; Wood *et al*., 2015; 2016) that have not yet been reported from Lowestoft.

The mytilid *Arcuatula senhousia* (Benson in Cantor, 1842), synonym *Musculista senhousia*, has been widely reported as a non-native species globally and has been given several vernacular names: Asian date mussel, Asian bag mussel, green mussel, Senhouse's mussel, Japanese mussel and nest mussel. Its native distribution has been described as extending from the Kuril Islands (Russian Far East) to Singapore (Cohen, 2005) and there are records for other parts of the Indo-Pacific region, including the Indian Ocean (Bosch *et al*., 1995). The type locality is Chusan (now Zhoushan), China (ca. 30°N). The species has been recorded as a non-native along the Pacific coast of North America between southern Canada and northern Mexico (Coan *et al*., 2000; Cohen, 2005), New Zealand (Creese, 1997) and southern Australia (Parry & Cohen, 2001). The first records for Europe were from Mediterranean France (Hoenselaar & Hoenselaar, 1989); it is now widespread in the wider region: Italy (Campani *et al.*, 2004), Tunisia (Ben Souissi *et al.*, 2005), Israel (Galil, 2007) and the Black Sea (Kovalev *et al.*, 2017). Current records for the Atlantic coast of Europe are from the Bay of Biscay, where it is known from the bassin d'Arcachon, France (Bachelet *et al.*, 2008; Laurent, 2007) and the Bidasoa and Nervión estuaries on the Basque coast, France and Spain (Bachelet *et al.*, 2008; Adarraga & Martinez, 2011). Despite recent increases in population and size ranges in the bassin d'Arcachon, the species does not yet appear to have extended its range in Atlantic France (N. Lavesque, pers. comm.). Previously unpublished Environment Agency data from Southampton Water, including the earliest (2011) records of *A. senhousia* for British waters, are presented here. The species was subsequently recorded from Southampton Water in 2017 (Holman *et al.*, 2019) and the nearby Solent, in 2017 and 2018 (Barfield *et al.*, 2018). There are many published accounts of severe problems caused by the arrival of *Arcuatula senhousia* in other regions. The mussels can form dense mats on soft substrata that alter the hydrology and sedimentology and can adversely affect filter-feeding bivalves (Galil *et al.*, 2008). However, they can increase diversity and populations of commercially important bivalves (*Venerupis* spp.) were unaffected in Italy (Galil *et al.*, 2008). Also, native predators have been shown to control populations in California (Reusch, 1998) and indigenous parasites have been recorded as able to transfer from native species to *A. senhousia* in New Zealand (Miller & Inglis, 2008), including pea crabs (*Pinnotheres* sp.) and copepods (Myicolidae), which have representative species in the UK. It may not be valid to consider every non-native species to be a serious threat without evidence (Reise *et al.*, 2006).

MATERIAL AND METHODS

In April 2018, an ecological survey was completed on Lake Lothing, as part of an impact assessment. The survey included collection of 54 grab samples, 42 wall scrape samples and 4 trawl samples. Samples were processed at APEM Ltd., following NMBAQC Scheme best practice guidelines (Worsfold and Hall 2010) and specimens from the samples are retained in the APEM voucher collection.

Samples were collected between 2011 and 2016 from Southampton Water, by the Environment Agency (EA) as part of a sampling programme for the Water Framework Directive. Details of the samples are summarised in Table 1. Localities are shown in Fig. 4.

Table 1 Records of *Arcuatula senhousia* (Benson in Cantor, 1842) from Southampton Water.

Latitude	Longitude	Water Depth (m)	Sampling Date	Sediment Description	No. of individuals
50°52'46.66''N	1°23'55.09''W	3.8	11/05/2011	Silt	6
50°53'27.81''N	1°24'39.24''W	6.81	11/05/2011	Silt	7
50°54'07.11''N	1°25'37.98''W	8.64	11/05/2011	Silt	3
50°54'20.96''N	1°23'09.49''W	4.68	11/05/2011	Silt	1
50°51'23.22''N	1°21'31.63''W	2.09	12/05/2011	Silt	1
50°52'27.44''N	1°22'05.54''W	7.46	09/06/2013	Mud	1
50°52'56.47''N	1°23'16.43''W	4.57	08/06/2013	Mud	1
50°53'01.71''N	1°24'13.22''W	5.32	09/06/2013	Mud	7
50°53'34.08''N	1°24'49.91''W	5.33	09/06/2013	Mud	1
50°53'36.57''N	1°23'15.44''W	10.58	09/05/2016	Mud	4
50°54'03.37''N	1°25'47.24''W	8.23	09/05/2016	Mud	29
50°52'54.93''N	1°24'03.27''W	6.64	09/05/2016	Mud	4
50°52'23.84''N	1°23'18.44''W	8.99	09/05/2016	Mud	1
50°52'06.82''N`	1°22'54.47''W	7.73	09/05/2016	Mud	1
50°52'54.87''N	1°23'15.07''W	4.69	09/05/2016	Mud	7
50°49'56.30''N	1°19'20.83''W	9.19	09/05/2016	Mud	3
50°52'43.98''N`	1°17'56.47''W	7.07	09/05/2016	Mixed/Mud	1
50°52'07.12''N	1°21'37.73''W`	6.22	09/05/2016	Mud	1

Results

In Lake Lothing *Theora lubrica* was collected from trawl samples (T01 and T02; Fig. 1) but not in the grab samples, which had an impoverished biota. Sediment types recorded for the area ranged from very slightly sandy mud to sandy mud; water depths ranged from 0 to 4.5m. Associated benthic species included *Crangon crangon* (Linnaeus, 1758), *Schistomysis kervillei* (GO Sars, 1885), *Palaemon serratus* (Pennant, 1777) and *Abra alba* (W Wood, 1802). The biotopes (Connor *et al*. 2004) recorded for the area were '*Aphelochaeta marioni* and *Tubificoides* spp. in variable salinity infralittoral mud' (SS.SMu.SMuVS.AphTubi; EUNIS A5.322) and 'Infralittoral fluid mobile mud' (SS.SMu.SMuVS.MoMu; EUNIS A5.324).

The intertidal region of the artificial harbour walls was observed to be colonized by aggregations of calcareous tubes. One of these aggregations was removed and the tubeworms identified in the laboratory as *Hydroides ezoensis*. The features required to identify this species are described by Sun *et al*. (2015). The walls were also colonised by another non-native species, the barnacle *Austrominius modestus*, which was found in all quadrat and wall scrape samples.

Other non-native and cryptogenic species were recorded from the grab samples. A spionid worm, provisionally identified as *Streblospio* sp., is likely to have been the non-native *S. benedicti* Webster, 1879. The cirratulid worm generally recorded as *Tharyx* 'species A' following Worsfold (2009) was found in many samples. Fragments of *Bugula neritina* were also recorded. The cryptogenic ascidian *Ascidiella aspersa* (Müller, 1776) was found in all trawl samples and was noted on the subtidal walls.

Specimens of *A. senhousia* were found in Environment Agency samples from Southampton Water (Table 1; Fig. 4). Numbers of individuals were not great, which could suggest that the introduction was recent or that the centre of distribution was not included in the sampling area. The region is well studied but it is not surprising to find either a recent or an overlooked introduction. The present authors have also recently identified specimens of *T. lubrica* from Southampton Water but precise collection data are not currently available for publication.

Description

Semelidae Stoliczka, 1870

Theora H. Adams & A. Adams, 1856

Theora lubrica Gould, 1861
(Figs 2 & 3)

Material examined One specimen Lake Lothing trawl sample T01 (Fig. 1; start: 52.47395°N, 1.736439°E; end: 52.47361°N, 1.738237°E; 18/04/2018); 26 specimens Lake Lothing trawl

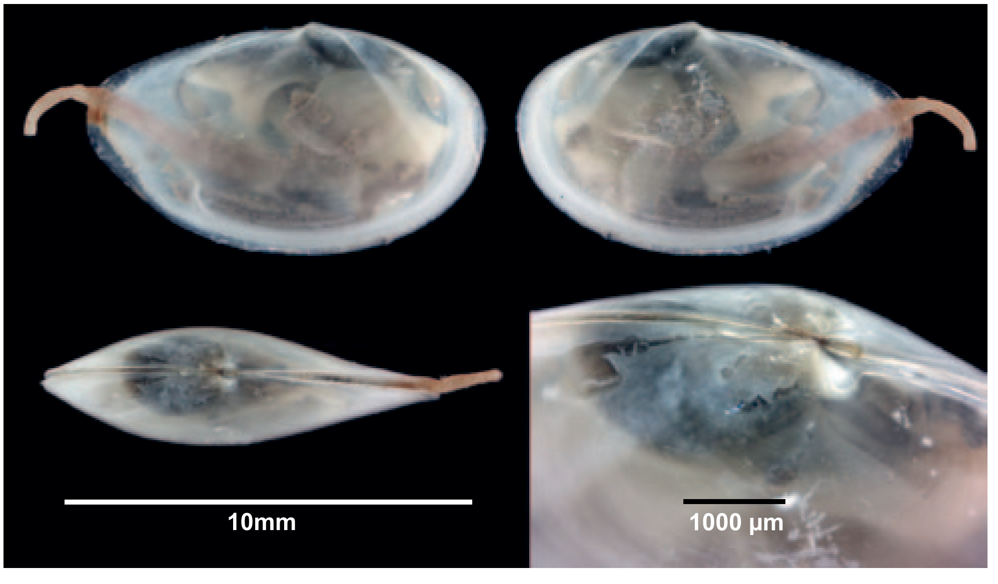

Figure 2 *Theora lubrica* Gould 1861; preserved 10mm specimen from Lake Lothing: (a), left valve; (b), right valve; (c), dorsal view; (d) details of umbonal region, from left valve. Scale bars=10mm (a, b, c) and 1.0mm (d).

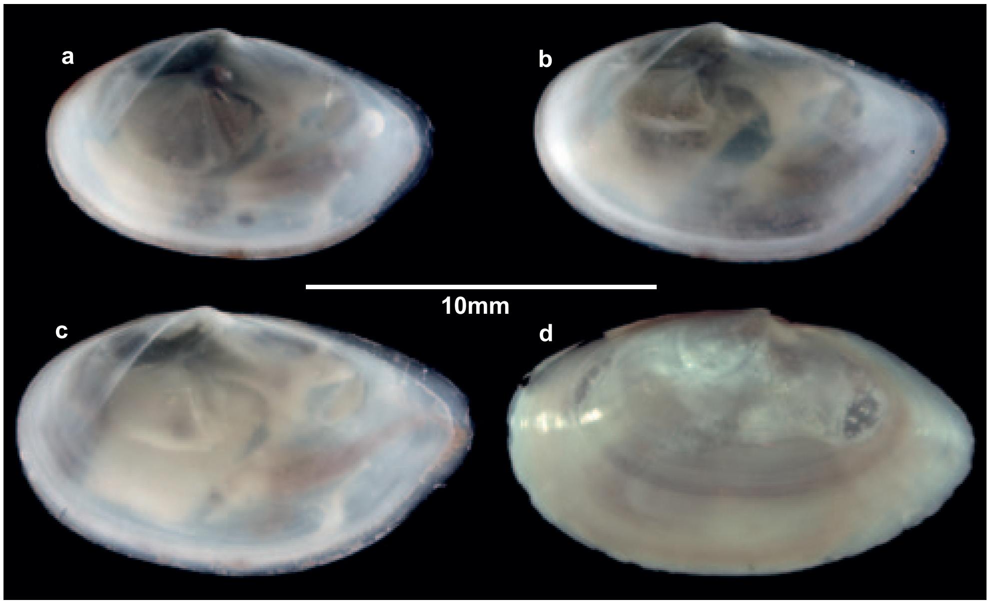

Figure 3 a–c *Theora lubrica* Gould 1861; preserved specimens from Lake Lothing: (a), 11mm specimen; (b), 12mm specimen; (c) 13mm specimen; (d) *Abra nitida* (O.F. Müller, 1776); preserved 14mm specimen from Strangford Lough.

sample T02 (Fig. 1; start: 52.47370°N, 1.736315°E; end: 52.47339°N, 1.738085°E; 18/04/2018).

Description Shell up to 16mm in length (observed Lowestoft specimens — to 13mm and 7mm in height). Thin, fragile, semi-transparent pearlescent white. Almost equivalve. Moderately compressed. Umbones about one third distance from anterior margin in large specimens; almost equilateral in smaller specimens. Outline ovate; posterior margin angular and drawn out into a slight beak-like form in larger specimens; anterior and ventral margins regularly curved; dorsal margin also regularly curved, except where punctuated by the umbones, which do not project significantly. Sculpture of fine concentric lines; periostracum very thin. Margin smooth. Thickened ridge on inner surface of each valve, extending obliquely from anterior hinge region to a short distance above the anterio-ventral margin. External ligament a short, brown band; internal ligament in a small, projecting chondrophore. Left valve with one small, bifid cardinal and single, weak laterals; right valve with two cardinals and single, weak laterals. Pallial sinus deep, extends to anterior of umbones, merges with pallial line. Internal anatomy partially visible through shell in preserved material. Subequal adductor muscles. Pair of long, reddish siphons extending about one third of shell length in preserved specimens. Ctenidium and foot visible but detail not discernible in available material.

Diagnosis The species is similar to native semelids, particularly *Abra nitida* (Müller, 1776), but has a conspicuous oblique internal rib, anteriorly, which was clear in the specimens examined from Lowestoft (Figs 2 and 3). The key recognition features of *T. lubrica* are described by Aderraga & Martínez (2011), who stated that the most similar *Abra* species have their beaks to the posterior, whereas *T. lubrica* has centrally placed beaks. We note that *Abra nitida* may have almost central beaks (Fig. 3d) whilst, in large *T. lubrica*, they are anteriorly placed, with the posterior region drawn out into a tapering projection (Fig. 3a–c). Also, *T. lubrica* is inclined to have valves that are more regularly rounded anteriorly, as compared with *Abra* species, and the external ligament is shorter and less pronounced. The shape differences are most pronounced in larger specimens, which are also more likely to have a slightly opaque surface that may obscure the internal rib. Faasse *et al.* (2019) describe internal identification features.

Discussion

The discovery of *Theora lubrica* in U.K. waters is perhaps unsurprising given the species' native

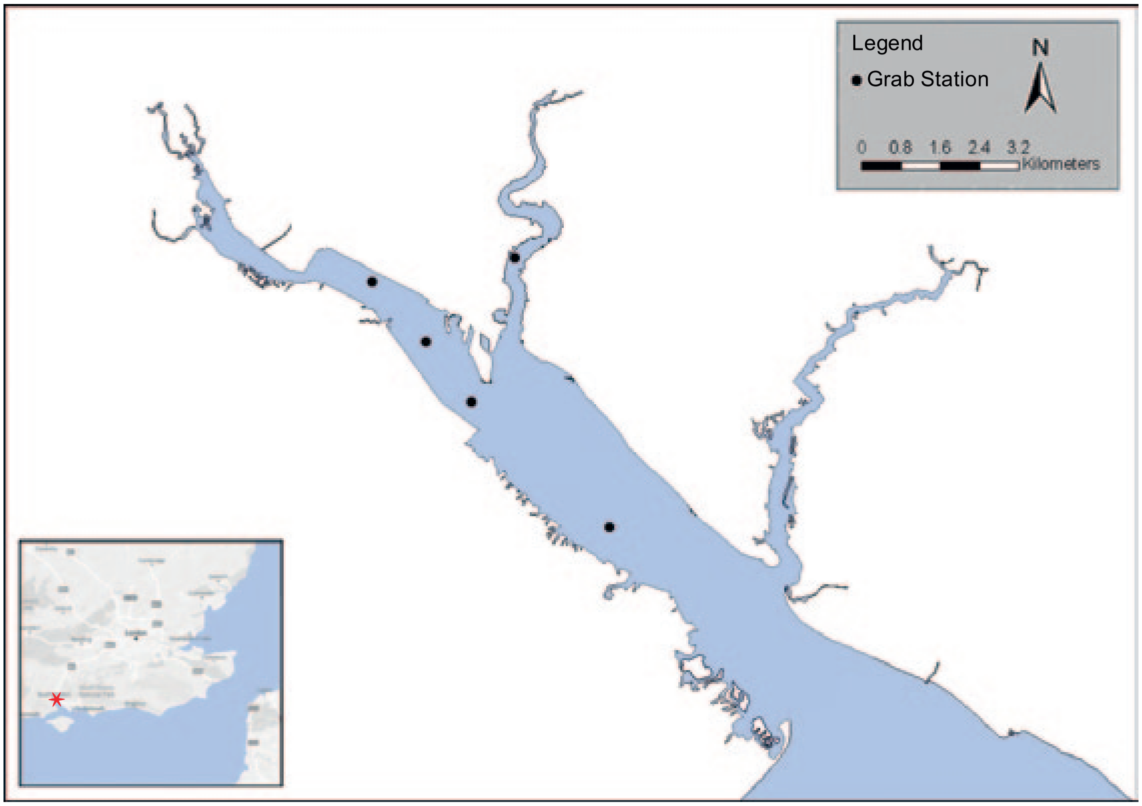

Figure 4 Map of Southampton Water showing locations of grab samples that included *Arcuatula senhousia* (Benson in Cantor, 1842) in 2011, 2013 and 2016.

range and capacity to colonise new areas as a non-native species. The Lowestoft record is the most northerly find for the species in Europe and a considerable distance (over 1,000km) from the previous Atlantic record (Nervion Estuary, Bay of Biscay; Adarraga & Martínez, 2011) but closer (200km) to the Dutch (delta area; Faasse *et al.*, 2019) records. The habitat fits the conditions in which *T. lubrica* is known to thrive and the species should be expected in other estuaries and sheltered muddy habitats across Europe. It is more surprizing that the first U.K. record should be from a relatively small port, when many non-native species are known from other estuaries with suitable conditions and more significant shipping activity. It is possible that the most recent surveys of these areas have not included the most suitable habitats for *T. lubrica* or that they have been misidentified in some projects. Our recent observation of the species in Southampton Water supports this interpretation and it is possible that review of archived material would reveal a different point of arrival to the U.K. However, it is also possible that Lowestoft is genuinely where the species first arrived in British waters. Lowestoft has some international shipping, which is the likely vector of introduction. Whilst the source of the population (native range or other area of introduction) is not certain, the Netherlands population, which has been present since at least 2003 (Faasse *et al.*, 2019), seems the most likely direct point of origin. Although it may spawn continuously throughout the year (Imabayashi, 1986), Imabayashi & Tsukada (1984) noted a decline in *T. lubrica* through the summer linked with low oxygen levels, suggesting that seasonality may be important to records of this species.

The other non-native species recorded for Lake Lothing are long-established in the U.K. and more widespread. *Austrominius modestus* was abundant on the walls and had also been noted previously (Bishop *et al.*, 2015; Wood *et al.*, 2016). The tubeworm *Hydroides ezoensis*, native to the northwest Pacific (Imajima, 1976), is known from the Solent (Thorp *et al.*, 1987) and was reported from Lowestoft by Wood *et al.* (2016), who did not remark on the range extension (most northerly in Europe to date); the present record confirms this occurrence. *Undaria pinnatifida* is also likely to have been a more recent introduction than *A. modestus*. Further work is required to establish the status of the cryptogenic species recorded. *Ascidiella aspersa* is usually omitted from reports of non-native species; it is widespread in U.K. waters and, if non-native, was most probably introduced many years ago. The soft-substratum species recorded are even less well-understood. *Streblospio benedicti* has only recently been recognised as part of the British fauna but many samples previously assumed to be the native *S. shrubsolii* (Buchanan, 1890), from several U.K. estuaries have proved to be this species (V. Radashevsky pers. comm.). Similarly, the *Tharyx* species most commonly found in British estuaries has been recognised as distinct from populations found in fully marine subtidal water since at least the 1990s. It is likely to be *T. robustus*, described from a small number of Swedish worms by Blake and Göransson (2015); we consider the species to be cryptogenic in the U.K. Further progress towards the resolution of these problems is planned for future work.

Barfield *et al*. (2018) presented records of *Arcuatula senhousia* from the Solent in 2017 and 2018, whilst Holman *et al*. (2019) also provided records from Southampton Water in 2017. Here we demonstrate that the species has been present in Southampton Water since at least 2011, bringing forwards the date of introduction of *A. senhousia* to British waters by more than 6 years. It is a small (up to 34mm in length), mussel, with a thin, partially ribbed shell, with green and brown markings and is relatively distinctive and is less likely to have been misidentified in routine samples than *T. lubrica*. In British waters, *A. senhousia* is most likely to be confused with native Mytilidae that also have radiating ribs across part of the shell. These include *Musculus discors* (Linnaeus, 1767), *M. costulatus* (Risso, 1826) and *M. subpictus* (Cantraine, 1835), also named *M. marmoratus* (Forbes, 1838) or *Modiolarca tumida* (Hanley, 1843). Whilst some mottling or variegation in colour pattern, often including shades of brown and green, can be found in all these species, the strong zigzag pattern over a green background is most distinctive in *M. costulatus* and *A. senhousia*. The ribs are less distinct and more numerous in *A. senhousia* and the shell outline is more elongate and asymmetrical.

The fauna associated with *A. senhousia* indicated subtidal muddy sand habitats, most of which were close to the biotope *Abra alba* and *Nucula nitidosa* in circalittoral muddy sand or slightly mixed sediment (SS.SSa.CMuSa.AalbNuc) of Connor *et al*. (2004), or EUNIS habitat A5.261. In the Bay of Biscay it can be found from intertidal to shallow water mud, gravel, *Zostera* and oyster beds and is tolerant of reduced salinities (Bachelet *et al*., 2008).

The findings presented here show the importance of species level records during routine surveys and the need for vigilance to allow the recognition of potential new non-native species records, in all areas but particularly in the vicinity of ports. Regular monitoring, using a variety of methods, will also help early detection of non-native species (Kakkonen *et al*., 2019). Published records, particularly of known fouling species or those with planktonic dispersal phases, for areas with similar climate and habitats serve as useful warnings of possible new finds. Global non-native species resources, such as checklists, horizon scanning exercises or 'species alerts', are a useful tool to alert biologists to the species likely to arrive in new areas in the future. The use of environmental DNA metabarcoding (Holman *et al*., 2019) may be of value if all sequences can be identified but currently suffers from the need to match against databases that may not be fully comprehensive; it is possible that this was the reason Holman *et al*. (2019) detected sequences of *A. senhousia* but not *T. lubrica* in Southampton Water.

There may have been some past complacency over species likely to colonize regions such as northern Europe caused by confusion over native ranges. For example, the Manila clam, *Ruditapes philippinarum* (Adams & Reeve, 1850), and Pacific oyster, *Magallana gigas* (Thunberg, 1793), have, at times, been listed as Indo-Pacific (warm water) fauna but, as with *Theora lubrica*, they are temperate north-west Pacific species, with the potential to spread throughout most of Europe. More research on the true native ranges of common estuarine species, globally, would greatly assist the prediction of future new non-native colonisations.

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