Research Article

First observation of the non-indigenous mysid *Neomysis americana* (S.I. Smith, 1873) in the Loire estuary

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Abstract

The non-indigenous mysid *Neomysis americana* (S.I. Smith, 1873) is reported here, for the first time, along the Bay of Biscay in the Loire estuary, France in 2021. This species, originating from North-American estuaries, was initially discovered in Europe in 2010 (Wadden Sea) and first reported in France in 2017 (Seine estuary). The absence of long-term monitoring makes it impossible to know precisely the arrival of this non-indigenous species in the Loire estuary. However, this species is present in high abundance, suggesting an arrival prior to 2021. Its introduction might even be prior to or concomitant to the Seine estuary discovery, suggesting an introduction via the ballast water of the commercial vessels.

Key words: introduction, Bay of Biscay, France, opossum shrimp, *Neomysis integer*, exotic species

Introduction

Estuaries are among the most productive aquatic systems and play an important trophic role as fish habitat (Beck et al. 2001). Many human activities (industries, fisheries, international maritime traffic) are concentrated in this multifaceted interface between sea, river, watershed and land. It is also a highly complex ecosystem where the spatial distribution of organisms depends on their ability to tolerate wide ranges of salinity and temperatures (Segal and Burbanck 1963; Somero 2005; Galván et al. 2016). These two parameters fluctuate at different time scales in estuaries with every flooding and ebbing tide, breach of the mouth, seasonal change in freshwater input, flood or drought (Elliott and McLusky 2002).

The abundance and diversity of organisms comprising the suprabenthos is used as an indicator of natural and anthropogenic changes in estuarine ecosystems (Cardoso et al. 2013; Dauvin et al. 2009). The suprabenthos corresponds to all organisms with the ability to migrate in the lower water layers (at night for example) with some contact with the seabed (during the day for example) (Beyer 1958; Brunel et al. 1978). It is dominated quantitatively by mysids that represent 95% of the total abundance in European estuaries (Cardoso et al. 2013; Rappé et al. 2011; Dauvin and Pezy 2013). *Neomysis integer* (Leach, 1814) is one of most abundant mysid species in European estuaries (> 95% of the collected suprabenthic individuals together with *Mesopodopsis slabberi* (Van Beneden, 1861)). It is the dominant prey for juvenile fishes in brackish waters (reviewed by Oliveira et al. 2023; Hostens and Mees 1999) and is found in over half of stomach contents of fish sampled in estuaries (Baldo and Drake 2002). *Neomysis integer* growth and development are triggered at 10 °C and, if the temperature is above 20 °C, its life cycle is accelerated (Fockedey et al. 2005, 2006).

The introduction of non-indigenous species is one of the most important factors endangering indigenous biodiversity in aquatic ecosystems (Rahel and Olden 2008) and is now considered to be the third largest cause of biodiversity decline in aquatic ecosystems (Sala et al. 2000; Molnar et al. 2008). One American invasive species, *Gammarus tigrinus* (Sexton, 1939) was first recorded in 2005 in the Loire estuary, France (Piscart et al. 2007) and is currently expanding into the Lower Loire and adjacent canals (Piscart et al. 2008). With its high reproductive potential and ability to exert a significant predation pressure on juvenile amphipods, combined with its tolerance to a broad range of environmental conditions, *G. tigrinus* can potentially outnumber native gammarids (Jänes et al. 2015). Furthermore, in a climate change context this invasive species has an increased food intake with higher temperatures, suggesting an increase in predation pressure affecting prey species as water temperatures rise (Pellan et al. 2016). *Neomysis americana* (S.I. Smith, 1873) was reported for the first time in Europe in 2010 in the Dutch Wadden Sea with only two specimens present in two Van Veen grabs (abundance of 10 individuals/m²), but one specimen was a female incubating postnauplioid larvae (Wittmann et al. 2012). In 2017, this species was observed in high abundance in the Seine estuary (Massé et al. 2018; Pezy et al. 2019). More recently, Soors et al. (2022) highlighted the presence of *N. americana* in Belgium (Schelde estuary) since 2012 with relatively high abundance.

Within the framework of the Biotrol project (Biodiversity and trophic relationships between benthos and fishes: 30 years of evolution in the Loire Estuary) in the Loire estuary, field surveys were organized on different biological compartments (meiobenthos, macrobenthos, suprabenthos and fish) to study the trophic web. The Loire estuary is a highly complex system which is under anthropogenic pressures originating from the fourth largest French maritime port (Grand Port Maritime de Nantes-Saint Nazaire), and urbanization or agricultural practices (Le Dez et al. 2017). During our recent study, numerous specimens of *N. americana* were found for the first time along the Atlantic coast of France in the Loire estuary. In this paper, we report and discuss this new observation along the French Atlantic coast.

Materials and methods

Study area

The length of the Loire estuary zone is about 97 km, including the tidally active zone in the upstream part for a surface area of 121 km^2 (Frankignoulle and Middelburg 2002). The flow rates of the Loire vary from 60 $m^3.s^{-1}$ during summer to more than 6,000 $m^3.s^{-1}$ during winter and spring floods, with an annual mean (2011–2021) of 825 $m^3.s^{-1}$ (https://www.hydro.eaufrance.fr/; accessed the 16th of May 2023). The Loire estuary is characterized by an important turbidity zone where levels of suspended matter can reach 1,000 $mg.L^{-1}$ (Relaxans et al. 1988). The salinity front (0.5 g/L) has moved upstream in the estuary by 60 km since 1900 due to bank adjustments, infillings and replenishment, but has been stable since 1990 (GIP Loire Estuaire 2002a). The influence of the tidal coefficient coupled with the Loire river flow creates a variable surface of tidal flats (from 625 to 2,710 hectares) with 50% of their surface area located in the first 12 km downstream (GIP Loire Estuaire 2002b).

Data collecting

The suprabenthos was sampled using three sledges (each with an 23 cm × 53 cm opening and 500 μm mesh) mounted on a modified beam trawl pole (manufactured by La Chaudrotechnique, Thouaré-Sur-Loire, France) and pulled against the current during 5 min at a speed of 1.5 knots. Three replicates were carried out at the same time, two for faunistic abundance and one for isotopic analyses. The suprabenthos was filtered out of the water at 0.05–0.25 m above the bottom and concentrated at the end of the net in a collector pot.

The suprabenthos was sampled during two seasons – spring (6 April 2021) and autumn (16 September 2021) in 15 stations with two replicates for each station (Figure 1). A total of 52 samples were analysed. Following the sampling, the net was washed on the boat to remove organisms via the collector. Then, all organisms were washed onto a 500 μm mesh sieve and preserved in 10% neutralised formaldehyde, before being identified and then transferred to a 70% ethanol solution.

Environmental parameters (water temperature, salinity, oxygen concentration and dissolved oxygen) were measured with an NKE SDOT300 sensor (manufacturer: NKE instrumentation) during the survey (data acquired from the 2nd, 7th and 8th April and from the 17th to 20th of September 2021) but not on the day of the beam trawl deployment.

Morphological description

Neomysis integer and *N. americana* (Figure 2A) can be distinguished by several morphological characters according to Wittmann et al. (2012), Massé et al. (2018) and Pezy et al. (2019).

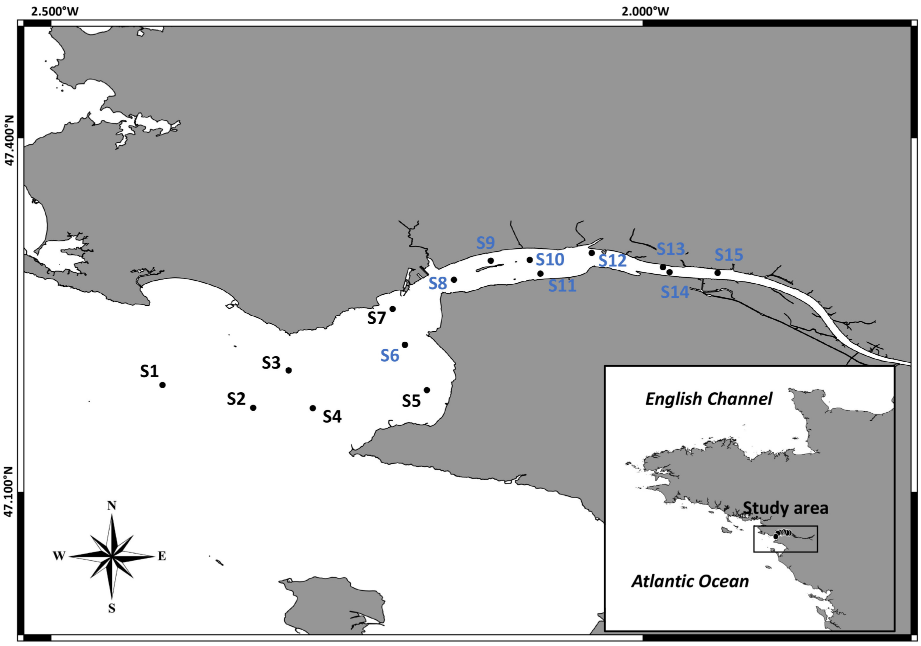

Figure 1. Map showing locations of suprabenthic samples in the Loire estuary. Stations in blue are where *Neomysis americana* (S.I. Smith, 1873) was found.

The telson for both *N. americana* and *N. integer* is long, narrow and triangular in shape. The telson is longer than the sixth abdominal somite and apex is narrow, truncate and armed with two pairs of spines without apical plumose setae. For *N. americana*, the lateral margins are armed by a continuous series of 20–43 spines, with the terminal half of the telson displaying groups of large spines with small spines in between (Figure 2C). For *N. integer*, the lateral margins are armed by a continuous series of 16–24 spines, crowded near the base and becoming gradually more spaced distally, more or less subequal in size, not arranged in series of larger spines with smaller ones in between. In addition, *N. americana* can be differentiated by a rounded rostrum and latero-distal pointed angle of the thorax (respectively white and black arrows, Figure 2B) (Massé et al. 2018).

A specimen is available at the Paris National Museum of Natural History under the collection number MNHN-IU-2022-452.

Results

According to Wittmann et al. (2012), Massé et al. (2018) and Pezy et al. (2019), the morphological characters allow the identification of the introduced mysid as *N. americana* (Figure 2). All specimens without clear adult morphologies or in bad morphological conditions were identify to genus level (*Neomysis* spp.).

A total number of 4,079 *N. americana,* 5,351 *N. integer* and 13,806 *Neomysis* spp. were collected with the suprabenthic sledge in the Loire estuary in 2021. In spring, 142 *N. americana* and 4,617 *N. integer* were collected, whereas, in autumn a total of 3,937 *N. americana* and 734 *N. integer* were collected. On both dates, *N. integer* and *N. americana* were present in

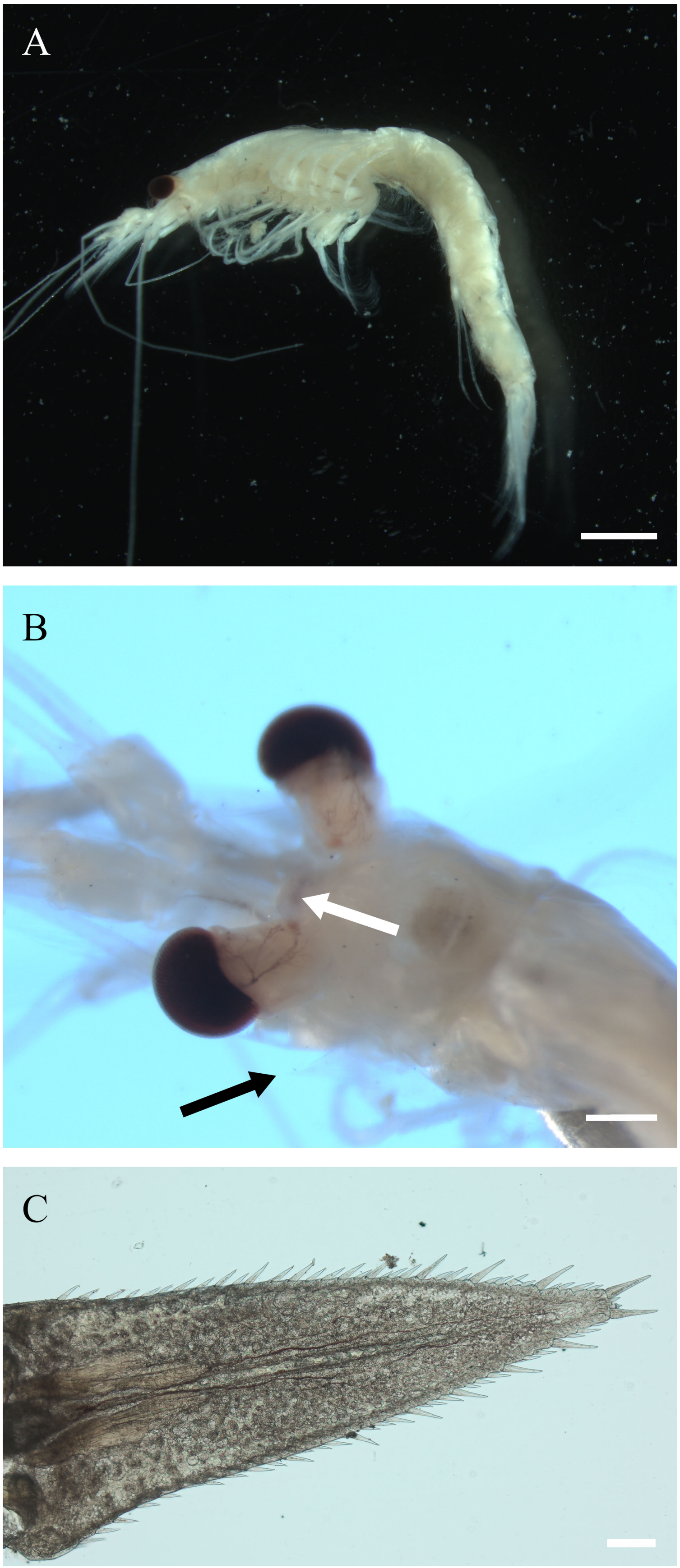

Figure 2. *Neomysis americana* (S. I. Smith, 1873) individual, profile (A), cephalothorax close-up, with white arrow showing the rounded rostrum and the black arrow showing the latero-distal pointed angle of the thorax (B) and telson (C) (MNHN-IU-2022-452). Scale bars: A: 2 mm; B: 500 µm; C: 200 µm. Photos taken by G. Droual.

Table 1. Mean abundances of *Neomysis americana* in the Loire estuary and abiotic parameters (Spri: Spring; Aut: Autumn).

Station	Abundance (in 100 m^3)		Temperature (°C)		Salinity		Oxygen (µmol.L^{-1})		Oxygen saturation (%)	
	Spri	Aut	Spri	Aut	Spri	Aut	Spri	Aut	Spri	Aut
S15	549.3 ± 275.6	2,604.5 ± 3,332.6	12.52	21.58	11.20	8.49	257.78	–	77.47	–
S14	–	1,080.8 ± 175.4	11.75	21.35	27.29	9.81	282.24	–	83.36	–
S13	–	2,197.0 ± 1,202.7	11.76	21.34	27.56	9.19	278.01	–	82.14	–
S12	–	70.9 ± 100.2	12.31	19.61	11.07	26.62	271.39	–	81.17	–
S11	70.9 ± 100.2	17.7 ± 25.1	12.66	19.25	12.45	22.71	228.26	–	68.83	–
S10	–	5,014.2 ± 5,988.6	12.43	19.26	20.57	24.14	246.64	–	74.00	–
S9	70.9 ± 100.2	283.5 ± 50.1	12.47	19.07	19.42	28.84	250.19	–	75.12	–
S8	–	17.7 ± 25.1	12.41	18.69	21.51	27.63	271.97	–	81.53	–
S7	–	–	11.71	19.01	27.79	28.93	297.17	–	87.67	–
S6	35.4 ± 50.1	17.7 ± 25.1	11.60	19.01	31.30	28.62	312.80	–	92.08	–
S5		–	11.63	19.16	31.63	32.54	327.43	–	96.43	–
S4		–	11.54	18.46	33.43	33.67	308.67	–	90.72	–
S3		–	11.53	18.04	33.02	33.91	303.30	–	89.12	–
S2	–	–	11.48	17.84	33.59	34.27	296.20	–	86.94	–
S1	–	–	11.41	17.59	33.26	33.99	303.77	–	88.99	–

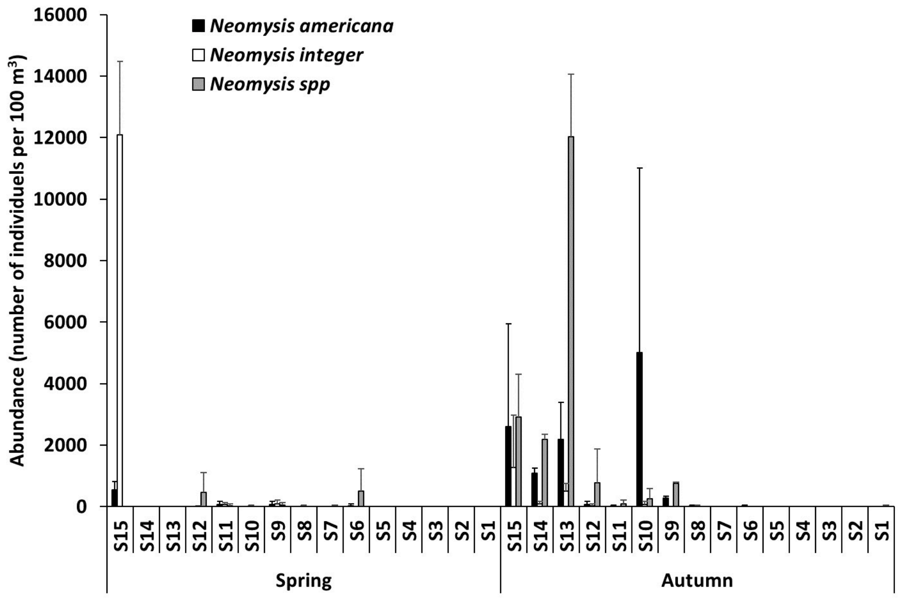

Figure 3. Density of *Neomysis americana* (S. I. Smith, 1873), *Neomysis integer* (Leach, 1814) and *Neomysis* spp. (ind. 100 m^{-3}) in the Loire estuary in spring and autumn 2021.

polyhaline and mesohaline zones, at salinities ranging from 8.49 (S15, Autumn) to 31.3 (S6, Spring) PSU (Table 1; Figure 1). For *N. americana*, the abundance at a single site ranged between 17.7 ± 25.1 (S6, S8, S11, Autumn) to 5,014.2 ± 5,988.6 (S10, Autumn) individuals per 100 m^3, whereas for *N. integer* between 17.7 ± 25.6 (S10, S8, Spring; S8, Autumn) and 12,101.4 ± 2,380.4 (S15, Spring) individuals were found per site per 100 m^3 (Figure 3). The suprabenthic community where *Neomysis* spp. specimens were observed was composed of mysids such as *M. slabberi*; *Schistomysis ornata* (G.O. Sars, 1864) and decapods *Palaemon longirostris* H. Milne Edwards, 1837; *Crangon crangon* (Linnaeus, 1758) and *Pinnotheres pisum* (Linnaeus, 1767).

Neomysis americana and *N. integer* are sympatric species and were abundant in the upper part of the Loire estuary (Figure 3).

Discussion

Since the first European observation in Dutch coastal waters (Wadden Sea) in 2010 (Wittmann et al. 2012), *N. americana* is continuing its spread in Europe. Two years later, this species was observed for the first time in the Belgian Scheldt estuary, but it may have been overlooked for some time (Soors et al. 2022). Five years after this second observation this species was recorded in the Seine estuary in relatively high abundance (Massé et al. 2018; Pezy et al. 2019) and has been present in the Western part of the bay of Seine (bay of Veys) since 2021 (J-P *personal observation*). However, as there is no long-term monitoring of the suprabenthos in the Loire estuary, it is difficult to determine the first occurrence of *N. americana* in this locality. As in other estuaries of the English Channel and south of the North Sea, we suggest an introduction via ballast waters (Massé et al. 2018; Pezy et al. 2019; Soors et al. 2022). The species is unlikely to have been introduced via aquaculture as only a very small mussel farm occurs at the estuary mouth (GIP Loire Estuaire 2003). Even if we cannot exclude a European dissemination by hull fouling, we hypothesize that *N. americana* has been introduced by ballast waters. Even though there is low inter-regional transport in the estuary (Alexandre et al. 2010), the Nantes Saint-Nazaire Port is the fourth largest maritime port in France, with more than 2,500 commercial cargos (oil tankers, roll-on ships, bulk carriers, container ships, gas tankers) in 2022 (https://www.nantes.port.fr, accessed the 13th of May 2023). Furthermore, the occurrences of *N. americana* are mainly in estuarine ecosystems in its native distributional range along the Atlantic coasts of the Americas (North and South) (Williams et al. 1974; Pezzack and Corey 1982; Calliari et al. 2007) and always in estuarine conditions in introduced areas (Wittmann et al. 2012; Massé et al. 2018; Pezy et al. 2019; Soors et al. 2022) (Figure 4). Due to a potential low tolerance to fully marine conditions, ballast waters are the most probable introduction pathway of *N. americana* in the Loire estuary.

In estuaries, mysids dominate the suprabenthic communities (Dauvin and Pezy 2013; Mauchline 1980). The genus *Neomysis* is particularly dominant from temperate to subarctic waters (Mauchline 1980) due to high salinity tolerance (Pezzack and Corey 1982; Roast et al. 1999). The maximum abundance of *N. americana* in the St. Lawrence (Canada, Northwest Atlantic) estuary was observed in the weakly stratified maximum turbidity zone (MTZ) of the estuarine transition zone (ETZ) for salinities between 0.6 to 8 PSU (Winkler et al. 2003; Bouchard and Winkler 2018). In the Río de la Plata (Argentina-Uruguay, Southwest Atlantic) estuary, *N. americana* was distributed within a broad salinity range (from 0.01

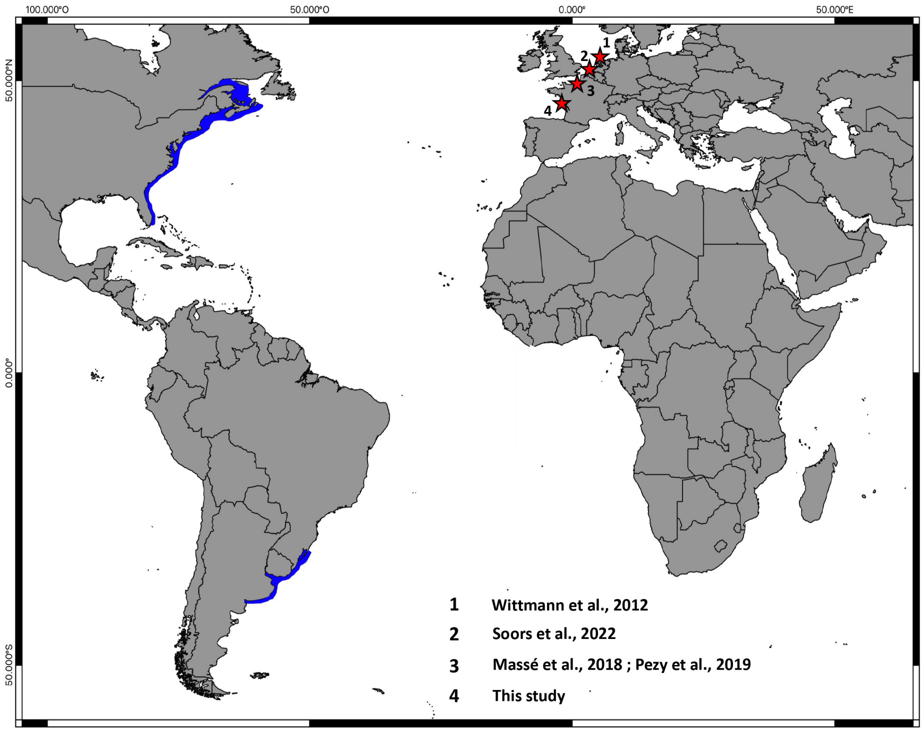

Figure 4. Worldwide distribution of *Neomysis americana* (S. I. Smith, 1873), with native regions in blue.

to 28 PSU). No significant relationship was identified between their abundance and salinity (Schiariti et al. 2006) despite individuals being often observed around the MTZ (Mianzan et al. 2001).

The opossum shrimp, *N. americana*, is the most abundant shallow living mysid inhabiting the coastal and estuarine waters of eastern United States, from 55 °N to 35 °N (Hopkins 1965; Wigley and Burns 1971; Williams et al. 1974; Corey 1988), corresponding to European latitudes. The abundance of *N. americana* in our study, with a maximum of 11,002 individuals per 100 m^3, remains low in comparison with other localities. For example, there have been reports of up to 250,000 individuals per 100 m^3 in the Río de la Plata estuary (Schiariti et al. 2006) and a maximum abundance of 330,000 individuals per 100 m^3 in the Indian River Inlet (Hopkins 1965). Consequently, this species is a major prey for several fish in its native range (Buchheister and Latour 2015), and, if its abundance increases drastically, this opossum shrimp might also become one of the main prey for fish in invaded estuaries.

Along the eastern coast of USA, when the temperature is 20 °C or more during the summer, three reproduction cycles per year can be expected. However, when the maximum temperature is below 20 °C, only two annual reproduction cycles occur (Viñas et al. 2005). With temperatures of 20 °C or more from June to September/October, the Loire estuary is highly suitable for *N. americana* reproduction (SYVEL 2022). Besides temperature, food availability is an important factor for its reproduction success.

The diet of *N. americana* is composed of copepods, such as *Eurytemora affinis affinis* (Poppe, 1880), *Halectinosoma curticorne* (Boeck, 1872), Cladocera, Rotifera, diatoms and pollen (Winkler et al. 2003). It is known that *E. affinis affinis* and *Evadne* spp. (Cladocera) occur in the Loire estuary (Rincé et al. 1989; Gabin Droual *personal observations*); thus, the introduced species does have prey present in the Loire estuary. As a potentially invasive species, we hypothesize that it could also predate on other indigenous species occurring in the estuary. The ability of this species to substantially increase its clearance rate and maintain high feeding rates at low prey densities (Fulton 1982), combined with its omnivorous diet could explain, in part, why the species maintains a high abundance throughout the year in its native distribution area (Viñas et al. 2005).

With temperatures suitable for completing its reproductive cycle and a satisfactory food availability, the colonization of the Loire estuary by *N. americana* comes as no surprise. With the high densities observed in two contrasted seasons, our study shows that *N. americana* can tolerate the environmental conditions of the Loire estuary. Further work on the population demography over a longer period of time is needed to confirm that this is a well established population in the Loire estuary. Due to its euryhaline nature, the native species *N. integer* avoids competition with other species by inhabiting the more environmentally challenging oligohaline zone (Vilas et al. 2006). Even if no studies have demonstrated the invasive character of *N. americana* in Europe, we highlight here that its high abundance may be important in introduced areas. Will *N. americana* outcompete *N. integer* populations or will *N. integer* mitigate competition by withdrawing in the oligohaline zone? More data are urgently needed in the future to determine the relation between these two opossum shrimp species.

Authors' contribution

GD and J-PP identified the interest to publish this record. RL participated to the fieldwork and environmental data acquisition. GD analysed samples. All authors read, improved and approved the final manuscript.

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Ethics and permits

All applicable international, national, and/or institutional guidelines for the care and use of animals were followed by the authors. All necessary permits for sampling and observational field studies have been obtained by the authors from the competent authorities and are mentioned in the acknowledgements, if applicable.

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