Research Article

The New Zealand mud snail *Potamopyrgus antipodarum* (J.E. Gray, 1853) (Tateidae, Mollusca) in the Iberian Peninsula: temporal patterns of distribution

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Abstract

Invasive exotic species (IES) are one of the most important threats to aquatic ecosystems. To ensure the effective management of these species, a comprehensive and thorough knowledge on the current species distribution is necessary. One of those species is the New Zealand mudsnail (NZMS), *Potamopyrgus antipodarum* (J.E. Gray, 1853) (Tateidae, Mollusca), which is invasive in many parts of the world. The current knowledge on the NZMS distribution in the Iberian Peninsula is limited to presence/absence information per province, with poor information at the watershed scale. The present study aims to: 1) update the distribution of NZMS in the Iberian Peninsula, 2) describe its temporal changes, 3) identify the invaded habitats, and 4) assess the relation between its abundance and the biological quality of fluvial systems. We reviewed the available information and found 352 records covering all main river basins. NZMS can be found over a wide range of environmental conditions and habitat types. The relation between the biological quality and the abundance of NZMS suggests that an intermediate biological quality is the optimum for NZMS. Our study shows that NZMS is in a spreading phase in the Iberian Peninsula, which makes its control very difficult, especially because of its non-water mediated dispersion mechanisms.

Key words: aquatic ecosystems, biological quality, invasive species, river, spread, stream

Introduction

Invasive exotic species (IES) are one of the most important threats to the functioning and diversity of aquatic ecosystems (Strayer 1999; Riley et al. 2008; Moorhouse and Macdonald 2015). These species reach new ecosystems generally thanks to human mediation, causing a homogenization of aquatic biotas (Havel et al. 2015; Petsch 2016). Invasion processes may alter the properties of invaded ecosystems and reduce the fitness of native species (Riley et al. 2008; Vinson and Baker 2008; Moorhouse and Macdonald 2015). Aquatic ecosystems are more susceptible to biological invasions than terrestrial ecosystems, due to several non-exclusive reasons: (1) they have less barriers to dispersal, (2) aquatic species exhibit a high intrinsic dispersal ability through longitudinal gradients, (3) there is a wide variety of pathways for introduction, and (4) the high level of human disturbance in aquatic ecosystems attracts biological invasions more than pristine systems (Lodge et al. 1998; Gherardi 2007; Moorhouse and Macdonald 2015). In the case of river communities, they have a high level of endemicity, especially for taxonomic groups with a low dispersal capacity in headwaters and isolated watersheds. This high endemicity makes communities vulnerable to the arrival of new invasive species lacking a common evolutionary history (Pérez-Bilbao et al. 2014; Ellender et al. 2015).

To ensure the effective management of IES, a comprehensive and thorough knowledge of the current species distribution at country or continental scale is necessary. Such information would allow allocating management efforts to the protection of ecosystems that are still uninvaded and to prevent future invasions (Lodge et al. 2006). Moreover, a detailed knowledge of the current IES distribution allows the construction of species distributions models (SDMs) for IES (Crespo et al. 2015). These models help anticipate the future distribution of the IES, identifying areas for future surveillances, and develop early detection and eradication plans (Olson et al. 2012; Gallardo and Aldridge 2013; Kaplan et al. 2014; Liang et al. 2014). Early detection of IES is needed to contain species before they become widespread and their control becomes unfeasible. Additionally, knowing the current distribution of IES is mandatory under several national and international laws, such as the Regulation 1143/2014 of the European Union or the RD 630/2013 of Spanish legislation. The latter specifies that the distribution and abundance of an IES must be part of the *strategy of management, control and possible eradication of an invasive exotic species*.

Among invasive groups, invertebrates often cause serious impacts to aquatic ecosystems, including alterations of water quality, nutrient dynamics, community structure, and the functioning of ecosystems (Matsuzaki et al. 2009; Higgins and Vander Zanden 2010; Pigneur et al. 2014; Gallardo et al. 2015; Lindim 2015). Among aquatic invertebrates, mollusks represent a group with a high diversity and an important ecological role (Strayer 1999; Brown 2001; Dillon 2004). Within mollusks, a high number of species has been considered as invasive in aquatic ecosystems (Karatayev et al. 2009). Several invasive mollusks have been profusely studied, such as the zebra mussel (*Dreissena polymorpha*), the apple snail (*Pomacea* spp.), and the Asian clam (*Corbicula fluminea*) (Lodge et al. 1998; Lowe et al. 2000; Aldridge et al. 2004; Carlsson and Lacoursiere 2005; Sousa et al. 2008; Higgins and Vander Zanden 2010). In contrast, other invasive mollusks have been less studied. This is the case of the New Zealand mudsnail (NZMS) *Potamopyrgus antipodarum* (J.E. Gray, 1853) (Tateidae, Mollusca). This species is a prosobranch gastropod that has been recently included in the Australasian family Tateidae (Wilke et al.

2013). It has a maximum shell size of 6–7 mm, reaching 12 mm in its native range in New Zealand (Winterbourn 1970). This small mollusk is termed "mud snail" since it is able to bury itself into the wet sediment during drought periods (Duft et al. 2003). It is also able to survive short periods of desiccation (Alonso and Castro-Díez 2012b). This gastropod has been reported to cause contrasting impacts on aquatic ecosystems (Alonso and Castro-Díez 2012a). For instance, in a stream of south-eastern of Australia, Schreiber et al. (2002) found a positive correlation between the density of NZMS and the density and richness of the native community. By contrast, in Polecat Creek (USA), NZMS monopolized the secondary production by consuming 75% of primary production and excreting 65% of the total NH_4^+ ecosystem (Hall et al. 2003). In fact, the influence of the native community structure on the invasion success of this species has not been studied so far. The ambiguous invasive behavior of NZMS may explain the poor availability of ecological knowledge. Alonso and Castro-Díez (2008) reviewed the factors that explain the invasion success of this species and highlighted a high fecundity, the parthenogenetic reproduction, the release from natural enemies, and the ability to tolerate a wide range of abiotic conditions. Moreover, this species has a very low susceptibility to parasites and predators in its non-native range (Alonso and Castro-Díez 2012a; Gérard et al. 2017). Although NZMS may be parasitised by up to 20 specific trematodes in its native range, which contributes to regulate the size of native populations (Prenter et al. 2004; Dunn et al. 2012), in Europe only one parasite has been identified so far (Zbikowski and Zbikowska 2009; Hechinger 2012; Gérard et al. 2003, 2017). Finally, the rate of survival of NZMS after passing the digestive system of predatory fish is relatively high (Aarnio and Bonsdorff 1997; Vinson and Baker 2008).

The watersheds of the Iberian Peninsula present a high degree of geographical isolation which promotes a high frequency of endemic species (Corbacho and Sánchez 2001; Pérez-Bilbao et al. 2014). However, human activities have overtaken these geographic barriers, causing an increase of biological invasions with catastrophic consequences for native biotas (Capinha et al. 2015). The current published information on the NZMS distribution in the Iberian Peninsula is limited to presence/absence information per province, with poor information at the watershed scale (Alonso and Castro-Díez 2015). Although additional information is available in the grey literature (e.g. technical reports, programs for water quality monitoring or local scientific publications), the temporal patterns of the species distribution in the Iberian Peninsula and its current distribution at watershed scale have not been sufficiently revised.

The present study focuses on: 1) producing an updated distribution map of NZMS in the Iberian Peninsula (continental part of Portugal and Spain) by means of a thorough review of available information, 2) describing temporal changes of NZMS distribution in the Iberian Peninsula, 3) identifying the main habitats invaded, and 4) assessing the relation between NZMS abundance and river's biological quality. This review contributes to improve the knowledge of this IES in the Iberian Peninsula, which provides a proper background to conduct management plans for this species.

Materials and methods

To compile a database with presences of NZMS in the Iberian Peninsula, a thorough search was conducted in databases of scientific literature (Web of Science, Scopus and JSTOR) with no restriction of publication year or kind type of document (thesis, scientific articles, reports, and books). The searching formula was: ("Iberian Peninsula" or "Spain" or "Portugal" or "España") AND ("Potamopyrgus antipodarum" or "New Zealand mudsnail" or "NZMS" or "mudsnail" or "mud snail" or "Potamopyrgus jenkinsi" or "Potamopyrgus"). Additionally, a subsequent search was conducted in Google (www.google.es) to find other non-scientific documents (technical reports, monitoring programs, water quality assessments, etc.). In this case the searching formula was ("Potamopyrgus antipodarum" or "New Zealand mudsnail" or NZMS or mudsnail or "mud snail" or "Potamopyrgus jenkinsi" or "Potamopyrgus" or "caracol del cieno") AND ("Iberian Peninsula" or "Spain" or "Portugal" or "España"). Moreover, the last part of the formula was subsequently changed by the names of the different main watersheds of the Iberian Peninsula, and by the name of Portugal and Spain Provinces and Autonomous Communities. Finally, the search was completed after contacting with experts who provided additional unpublished reports of monitoring carried out by local administrations. The date of search was May 2017. The total number of retrieved documents was 1256. Among them, documents containing georeferenced presences of NZMS (geographical coordinates and/or description of the study area) were selected. When geographical coordinates were not available, but the location was precisely described by the authors, we used https://maps.pixelis.es (Version 1.0.7 API Google Maps 3.26) to obtain the coordinates of the site. When available, we also collected information on the ecosystem type (river, stream, irrigation channel, lake, ravine, spring, marsh, coastal lake, pond, estuary, other), physical and chemical water properties (pH, electric conductivity, etc.), and abundance of NZMS. Finally, the year when each presence was reported was also added to our dataset. The total number of documents with useful information (i.e. at least with available information on the geographical location of this species) for this study was 62. Additional records (N = 28) were obtained from the Global Biodiversity Information Facility (www.gbif.org). All presences of NZMS were used in ArcGIS 10.3® to generate a map of the distribution of the species.

The cumulative number of records of NZMS in the Iberian Peninsula was calculated from the first record (1924) (Orozco et al. 2001) to the last

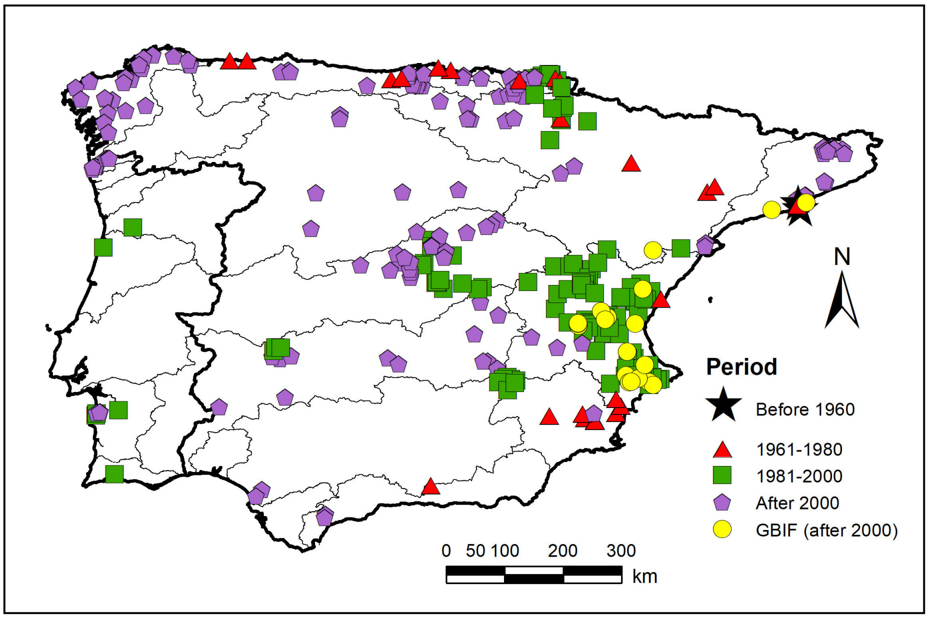

Figure 1. Current distribution of *Potamopyrgus antipodarum* (NZMS) in the Iberian Peninsula, with the oldest records illustrated with big black stars. Different colors indicate different recording periods. NZMS records from the Global Biodiversity Information Facility (GBIF) are shown in cream-colored circles.

one (2015) (Clusa et al. 2016). Additionally, the total number of records was calculated for each type of invaded ecosystems (river, stream, irrigation channel, lake, ravine, spring, marsh, coastal lake, pond, estuary, other).

We tested the relationship between the relative abundance of NZMS in the macroinvertebrate community and the biological quality of aquatic ecosystems, using a dataset from García Bernadal and Romero Suánces (2006), who monitored 34 sampling points twice (spring and autumn) in 2005, distributed through Galicia, NW of Spain. In each sampling point the authors used a D-net sampler taking 20 kicks in a stretch of 100 m to identify macroinvertebrate species and their relative abundance (%). Besides, they estimated the biological quality in a scale of 6 (1 = bad, 6 = very good) by comparing the current macroinvertebrate community with the "ideal one" (i.e. the theoretical community present in a natural non-altered fluvial ecosystem with similar properties). The abundance of NZMS in those sampling points ranged from 0 to 80 percent of the macroinvertebrate community. Using a polynomic model, we adjusted the relative abundance of NZMS in the community and the biological quality index across sampling points, using for each one the average value between the two sampling seasons. Additionally, the percentage of sampling points where NZMS was absent was calculated for each value of biological quality. This analysis was performed with the *lm* function in RStudio version 1.3.383.

Results

We collected a total of 352 records of NZMS in the Iberian Peninsula, most of which were not previously covered by GBIF (Figure 1) (Supplementary material Table S1). NZMS has been recorded in both Spain (339 records)

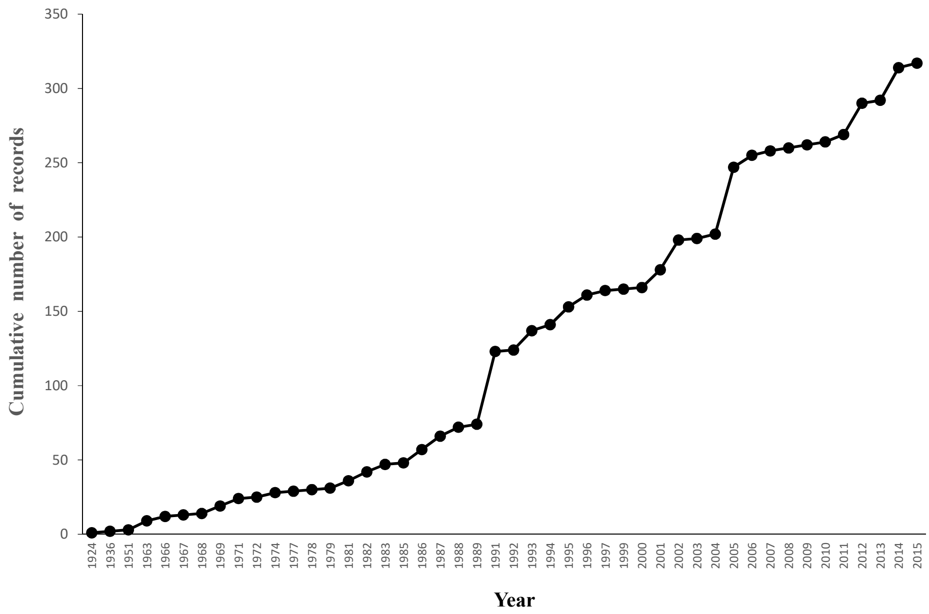

Figure 2. Temporal trend of the cumulative number of records of *Potamopyrgus antipodarum* in the Iberian Peninsula.

and Portugal (9 records); four records were shared by the two countries in the Miño-Sil River (northern border between the two countries). The NZMS has been recorded in all 12 main watersheds, with the highest number of records in the Júcar watershed -east Iberian Peninsula (89 records), Cantábrico watershed -north Iberian Peninsula (60 records), and Ebro watershed -northeast Iberian Peninsula (54 records). In general, there were more records in the central, eastern and northern watersheds of the Iberian Peninsula than in western and southern watersheds (Figure 1).

NZMS was recorded for the first time in 1924 in the Llobregat Delta (province of Barcelona in the northeast of Spain) and the last record was in 2015 in the Nora River (province of Asturias, north Spain). The cumulative number of records of NZMS in the Iberian Peninsula increased with time (Figure 2). Although the increase is quite steady, there are two clear steps, 1991 and 2005. The first increase may be attributed to the increase of scientific studies on fluvial ecology in the Iberian Peninsula, and the second may be the result of the application of the European Water Framework Directive. Rivers and streams showed the highest number of records, followed by irrigation channels (Figure 3), the three of them making up 91.3% of the records; therefore, the lotic freshwater ecosystems seem to be the main habitats for this species in the Iberian Peninsula.

In general, NZMS can be found over a wide range of environmental conditions (Table 1). The altitude ranges from 0 to 1529 meters above sea level (masl), with an average of 377.9 m. The maximum height was recorded in the upper Turia River (Júcar watershed, Province of Teruel, Spain) (Pérez-Murciano et al. 1998). The pH of NZMS locations ranged from 6.4 to 9.2, with a mean value of 8.16 (n = 53), which indicates a preference for alkaline waters. The electric conductivity ranged from 63.5 to 11,450 µS/cm,

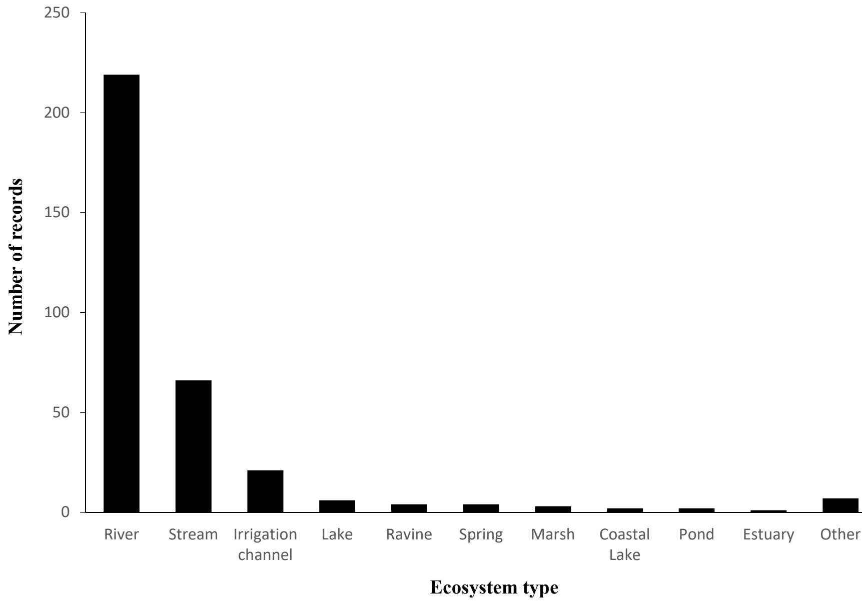

Figure 3. Cumulative number of records of *Potamopyrgus antipodarum* for each type of habitat (river, stream, irrigation channel, lake, ravine, spring, marsh, coastal lake, pond, estuary and other) in the Iberian Peninsula.

Table 1. Environmental properties that have been reported for the records of *Potamopyrgus antipodarum* in the Iberian Peninsula. Minimum, maximum, mean and number of records (n) are presented for each environmental property.

	Min	Max	Mean	n
Height above sea level (m)	0	1529	377.9	352
pH	6.4	9.2	8.16	53
Conductivity (µS/cm)	63.5	11450	847.8	61
Abundance (individuals/m^2)	1	98300	5187.7	49

the later corresponding to a saline coastal lake (Costa et al. 2003; Correia et al. 2012). However, the mean conductivity was 847.8 µS/cm (n = 61) with a standard deviation of 1465.2. We found 49 samples with conductivity lower than 1000 µS/cm, indicating a preference for freshwater environments. Abundance of NZMS ranged from 1 to 98,300 individuals per square meter, with a mean value of 5,188 (n = 49) (Table 1).

The relation between the biological quality of the stream and the relative abundance of NZMS in Galicia suggests that an intermediate biological quality (between 2 and 3) is the optimum for NZMS, whose proportion declines at both extremes of biological quality. However, the model has a high uncertainty in the low quality extreme due to the low number of points (Figure 4). When only presence/absence was considered, we found that NZMS was absent in 75, 50, 28.6, 42.9, 71.4 and 90.9% of the sampling points with biological quality from 1 to 6, respectively. Thus, fewer absences where found at points with intermediate biological quality of 3–4.

Discussion

NZMS distribution and temporal patterns in the Iberian Peninsula

The major focus of this work was to update the knowledge on *Potamopyrgus antipodarum* distribution in the Iberian Peninsula. Our review added 324

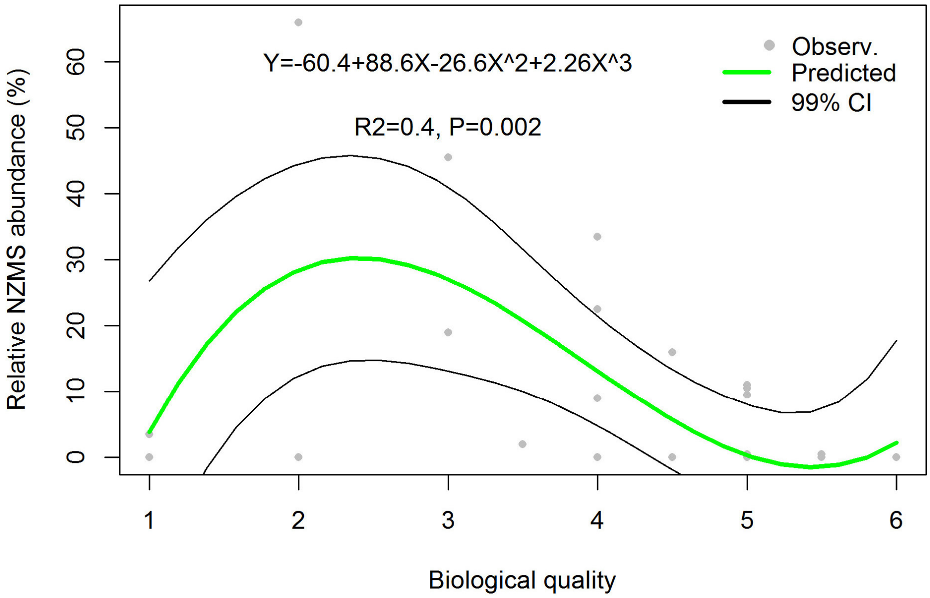

Figure 4. Relation between the index of biological quality and the relative abundance of *Potamopyrgus antipodarum* in a sampling in Galicia performed by García Bernadal and Romero Suánces (2006). The polynomial function (green line ± 99% confidence intervals), R^2 and significance of the adjustment are shown.

records to the 28 previously available in the Global Biodiversity Information Facility (GBIF). Moreover, most of the GBIF records were located in the eastern coast of Spain, but our revision has shown a wider distribution, expanding north- south- and westwards to cover the full Iberian Peninsula. Thus, our review represents a significant step forward in the knowledge of NZMS distribution.

Older records of NZMS are mostly located in the coastal area (see reviews of Ibáñez and Alonso 1977; Simoes 1988; Alonso and Castro-Díez 2015, and Figure 1), suggesting that the first individuals arrived by ship, either in ballast waters or water tanks. The fact that the first record (Delta del Llobregat 1924) is very close to the port of Barcelona, an important hub for maritime traffic in the Mediterranean Sea, supports this hypothesis. In fact, other authors reported that water tanks carried by ships were the main pathway for entrance of this species in Europe (Thames estuary in the nineteenth century) (Ibáñez and Alonso 1977). From this entrance point in Europe, NZMS was suggested to subsequently spread by waterfowl towards central Europe (Ibáñez and Alonso 1977; Butkus et al. 2014). Waterfowl may have also been the main pathway for inland spread in the Iberian Peninsula, considering that many routes of bird migration between Europe and Africa cross the Iberian Peninsula (Pérez-Tris and Santos 2004). This fact may have contributed to increase the risk of NZMS invasion throughout the aquatic ecosystems of the Iberian Peninsula, especially in lentic ones. A model developed by van Leeuwen et al. (2012) estimates that, on average, waterfowl may disperse up to five-six viable propagules (either animals or plants) after flying more than 100–300 km. In the case of NZMS, van Leeuwen and van der Velde (2012) showed that this snail can be passively transported in the bill of mallard (*Anas platyrhynchos*). Fishing tools and boats may represent additional vectors for NZMS dispersal. These dispersion vectors are supported by the fact that NZMS has a high tolerance to air exposure and to subsequent translocation to a new fluvial ecosystem (Alonso and Castro-Díez 2012b; Alonso et al. 2016). Once in a new watershed, NZMS may be further dispersed by fish (Bruce and Moffitt 2009). Thus, the spread from coastal areas to inner locations is likely mediated, among others, by animals, including fish carrying NZMS in their digestive tracts.

In the 1961–1980 period, NZMS spread upstream through the Ebro (north and north-east) and Júcar (south-east) rivers and appeared in the Cantabrian coast (north). The colonization of the latter may have occurred again by ship traffic, given the existence of several routes joining Cantabrian ports (Santander, Bilbao) with UK ports (Plymouth, Porstmouth), the country where the species appeared for the first time in Europe. During the next period (1981–2000), NZMS appeared for the first time in Portugal in the lowest part of Duero River. In the last period (after 2001), new records appeared in central Spain and western of the Iberian Peninsula (both Portugal and Spain). The high number of records in Galicia derives from an intensive monitoring carried out in 2005 (García Bernadal and Romero Suánces 2006), but the species may have been present there before. This latter colonization of the west coast of the Iberian Peninsula may have started from maritime ports or from the expansion of the invasion front westwards.

Habitat preferences and conservation

Although NZMS can dwell in different types of aquatic environments, most of the records were found in lotic ecosystems. These ecosystems are profusely monitored by water management authorities from different political administrations (both national and regional), which provide long-term data series, especially of physico-chemical data. Biological monitoring has been later developed for watersheds since the European Union Water Framework Directive (Directive 2000/60/CE) came into effect. Additionally, natural lotic ecosystems are more common than natural lentic ones in the Iberian Peninsula, and they suffer from an intense human management (Lorenzo-Lacruz et al. 2012; Vidal-Abarca and Suárez 2013). Although human-disturbed ecosystems have been considered to be more prone to biological invasions (Johnson et al. 2008; Karatayev et al. 2009; Clavero and Hermoso 2011), we found that both well-preserved and impacted ecosystems are colonized by NZMS. For instance, Álvarez-Cabria et al. (2011) found NZMS in stretches affected by the effluents of wastewater treatment plants in rivers of north Spain, and Serrano et al. (2004) found this species in a lagoon with a very poor water quality in the southwest of Spain. By contrast, several authors found NZMS in well-preserved ecosystems of the Iberian Peninsula (del Moral et al. 1997; Álvarez-Cabria et al. 2011). This has also been reported for other Mediterranean regions (Mazza et al. 2011).

Wide range of abundance of NZMS in the Iberian Peninsula

We found a huge range of NZMS densities in our dataset, ranging from 1 to 98,300 individuals per square meter (Martínez-Ortí et al. 2004; Rolán 2004; Álvarez-Cabria et al. 2010, 2011). Previous studies suggest that the high dominance of NZMS in some invaded communities may be attributed to a wide tolerance to physical-chemical factors, to a high ability to compete at early stages of succession, and to the low control that predators and parasites exert on NZMS populations (Alonso and Castro-Díez 2008; Gérard et al. 2017). By contrast, low densities may be attributed to a low residence time (Moore et al. 2012), and/or to the high biotic pressure exerted by the native community in well-preserved ecosystems. In fact, our analysis relating NZMS relative abundance and biological quality suggests that streams with intermediate biological quality support the highest relative abundances of NZMS. This is in accordance with a previous study that shows an intermediate tolerance of NZMS to biodegradable pollution (Mouthon and Charvet 1999), which is a factor directly associated with the biological quality of streams (Rosenberg and Resh 1993). Thus, NZMS populations may be limited by unsuited abiotic conditions in highly polluted waters, and by biotic pressures exerted by the native community in high-quality waters. However, some well-preserved ecosystems (= high biotic pressure) also present a high abundance of NZMS, which shows the complexity of that relation (del Moral et al. 1997; Mazza et al. 2011). Additionally, the residence time may be an important factor to determine the NZMS density, as longer residence time could cause the collapse of NZMS populations (Moore et al. 2012).

Implications for management

NZMS has been included in the list of invasive exotic species of the Spanish legislation (Royal Decree 630/2013). This implies an obligation to monitor the species distribution and abundance in order to develop a mandatory *Strategy of Management, Control and Possible Eradication of an Invasive Exotic Species*. Our results show that NZMS is widely spread through the Iberian Peninsula, which represents an important handicap to control and avoid dispersion, and makes its eradication impossible. Several strategies and methodologies have been described in the bibliography for the control and eradication of NZMS, both in natural ecosystems and in aquaculture facilities (McMillin and Trumbo 2009; LeClair and Cheng 2011; Stockton-Fiti and Moffitt 2017). However, the likely importance of natural dispersion (fish, waterfowl, etc.), together with the small size of this species, represents an obstacle to apply these methods in natural ecosystems, especially in fluvial ones. Thus, we suggest that Administrations should focus their efforts on preventing further spread rather than in eradication, implementing measures, such as disinfection of fishing tools or boats, or banning the use of live baits.

Conclusions

Our study has shown that the invasive species *P. antipodarum* is present in the 12 main watersheds of the Iberian Peninsula. This species has colonized diverse ecosystems, including natural habitats (rivers, streams, lakes, coastal lagoons, etc.) and artificial ones (irrigation channels), from freshwater to saltwater. Our review shows that this species is in a clear spreading phase in the Iberian Peninsula, which makes its control very difficult, especially because of its non-water mediated dispersion mechanisms. Although its ecological impact has been clearly demonstrated, the main factors that control the density of NZMS in invaded ecosystems are not clear. Our results suggest that the relative abundance of NZMS is limited by both high and low biological quality of streams.

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References

Aarnio K, Bonsdorff E (1997) Passing the gut of juvenile flounder, *Platichthys fesus* (L.)– differential survival of zoobenthic prey species. *Marine Biology* 129: 11–14, https://doi.org/10.1007/s002270050140

Aldridge DC, Elliott P, Moggridge GD (2004) The recent and rapid spread of the zebra mussel (*Dreissena polymorpha*) in Great Britain. *Biological Conservation* 119: 253–261, https://doi.org/10.1016/j.biocon.2003.11.008

Alonso A, Castro-Díez P (2008) What explains the invading success of the aquatic mud snail *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca)? *Hydrobiologia* 614: 107–116, https://doi.org/10.1007/s10750-008-9529-3

Alonso A, Castro-Díez P (2012a) The exotic aquatic mud snail *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca): state of the art of a worldwide invasion. *Aquatic Science* 74: 375–383, https://doi.org/10.1007/s00027-012-0254-7

Alonso A, Castro-Díez P (2012b) Tolerance to air exposure of the New Zealand mudsnail *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca) as a prerequisite to survival in overland translocations. *NeoBiota* 14: 67–74, https://doi.org/10.3897/neobiota.14.3140

Alonso A, Castro-Díez P (2015) El caracol acuático neozelandés del cieno (*Potamopyrgus antipodarum*): impactos ecológicos y distribución de esta especie exótica en la península ibérica. *Ecosistemas* 24: 52–58, https://doi.org/10.7818/ECOS.2015.24-1.09

Alonso A, Valle-Torres G, Castro-Díez P (2016) Survival of an invasive aquatic snail to overland translocation in non-aquatic media: Implications for spreading. *Limnologica* 57: 60–65, https://doi.org/10.1016/j.limno.2016.01.002

Álvarez-Cabria M, Barquin J, Antonio Juanes J (2010) Spatial and seasonal variability of macro invertebrate metrics: do macroinvertebrate communities track river health? *Ecological Indicators* 10: 370–379, https://doi.org/10.1016/j.ecolind.2009.06.018

Álvarez-Cabria M, Barquín J, Juanes JA (2011) Microdistribution patterns of macroinvertebrate communities upstream and downstream of organic effluents. *Water Research* 45: 1501–1511, https://doi.org/10.1016/j.watres.2010.11.028

Brown KM (2001) Mollusca: Gastropoda. In: Thorp JH, Covich AP (eds), Ecology and Classification of North American Freshwater Invertebrates, 2nd Edition, Academic Press, San Diego, pp 277–307, https://doi.org/10.1016/B978-012690647-9/50011-9

Bruce RL, Moffitt CM (2009) Survival and passage of ingested New Zealand Mudsnails through the intestinal tract of rainbow trout. *North American Journal of Aquaculture* 71: 287–301, https://doi.org/10.1577/A08-033.1

Butkus R, Sidagyte E, Rakauskas V, Arbaciauskas K (2014) Distribution and current status of non-indigenous mollusc species in Lithuanian inland waters. *Aquatic Invasions* 9: 95–103, https://doi.org/10.3391/ai.2014.9.1.08

Capinha C, Essl F, Seebens H, Moser D, Pereira HM (2015) The dispersal of alien species redefines biogeography in the Anthropocene. *Science* 348: 1248–1251, https://doi.org/10.1126/science.aaa8913
Carlsson NOL, Lacoursiere JO (2005) Herbivory on aquatic vascular plants by the introduced golden apple snail (*Pomacea canaliculata*) in Lao PDR. *Biological Invasions* 7: 233–241, https://doi.org/10.1007/s10530-004-0741-4
Clavero M, Hermoso V (2011) Reservoirs promote the taxonomic homogenization of fish communities within river basins. *Biodiversity and Conservation* 20: 41–57, https://doi.org/10.1007/s10531-010-9945-3
Clusa L, Ardura A, Gower F, Miralles L, Tsartsianidou V, Zaiko A, García-Vázquez E (2016) An easy phylogenetically informative method to trace the globally invasive *Potamopyrgus* Mud Snail from River's eDNA. *PLoS ONE* 11: 1–16, https://doi.org/10.1371/journal.pone.0162899
Crespo D, Dolbeth M, Leston S, Sousa R, Pardal MA (2015) Distribution of *Corbicula fluminea* (Müller, 1774) in the invaded range: a geographic approach with notes on species traits variability. *Biological Invasions* 17: 2087–2101, https://doi.org/10.1007/s10530-015-0862-y
Corbacho C, Sánchez JM (2001) Patterns of species richness and introduced species in native freshwater fish faunas of a Mediterranean-type basin: the Guadiana River (southwest Iberian Peninsula). *Regulated Rivers: Research and Management* 17: 699–707, https://doi.org/10.1002/rrr.631
Correia MJ, Costa JL, Chainho P, Félix PM, Chaves ML, Medeiros JP, Silva G, Azeda C, Tavares P, Costa A, Costa AM, Bernardo J, Cabral HN, Costa MJ, Cancela da Fonseca L (2012) Inter-annual variations of macrobenthic communities over three decades in a land-locked coastal lagoon (Santo André, SW Portugal). *Estuarine, Coastal and Shelf Science* 110: 168–175, https://doi.org/10.1016/j.ecss.2012.04.028
Costa AM, Cristo M, Cancela da Fonseca L (2003) Annual cycle of the benthic community of a coastal lagoon: Lagoa de Melides (Grândola, SW Portugal). *Revista Biologia (Lisboa)* 21: 71–89
Del Moral M, Martínez-López F, Pujante AM (1997) Estudio de los peque-os ríos de la Sierra de Espadan (SO de Castellón). Macroinvertebrados y calidad de sus aguas. *Ecología* 11: 37–61
Dillon RT (2004) The Ecology of Freshwater Molluscs. Cambridge University Press, Cambridge, 509 pp
Duft M, Schulte-Oehlmann U, Tillman M, Markert B, Oehlmann J (2003) Toxicity of triphenyltin and tributyltin to the freshwater mud snail *Potamopyrgus antipodarum* in a new sediment biotest. *Environmental Toxicology and Chemistry* 22: 145–152
Dunn AM, Torchin ME, Hatcher MJ, Kotanen PM, Blumenthal DM, Byers JE, Coon CAC, Frankel VM, Holt RD, Hufbauer RA, Kanarek AR, Schierenbeck KA, Wolfe LM, Perkins SE (2012) Indirect effects of parasites in invasions. *Functional Ecology* 26: 1262–1274, https://doi.org/10.1111/j.1365-2435.2012.02041.x
Ellender BR, Woodford DJ, Weyl OLF (2015) The invisibility of small headwater streams by an emerging invader, *Clarias gariepinus*. *Biological Invasions* 17: 57–61, https://doi.org/10.1007/s10530-014-0744-8
Gallardo B, Aldridge DC (2013) Priority setting for invasive species management: integrated risk assessment of multiple Ponto Caspian invasive species into Great Britain. *Ecological Applications* 23: 352–364, https://doi.org/10.1890/12-1018.1
Gallardo B, Clavero M, Sánchez MI, Vilà M (2015) Global ecological impacts of invasive species in aquatic ecosystems. *Global Change Biology* 22: 151–163, https://doi.org/10.1111/gcb.13004
García Bernadal MT, Romero Suánces R (2006) Seguimiento del estado de calidad de la red de aforos de Galicia-Costa basándose en la fauna de macroinvertebrados acuáticos: año 2005. Universidad de Santiago de Compostela, España. Technical Report, 95 pp
Gérard C, Blanc A, Costil K (2003) *Potamopyrgus antipodarum* (Mollusca: Hydrobiidae) in continental aquatic gastropod communities: impact of salinity on trematode parasitism. *Hydrobiologia* 493: 167–172, https://doi.org/10.1023/A:1025443910836
Gérard C, Miura O, Lorda J, Cribb TH, Nolan MJ, Hechinger RF (2017) A native-range source for a persistent trematode parasite of the exotic New Zealand mudsnail (*Potamopyrgus antipodarum*) in France. *Hydrobiologia* 785: 115–126, https://doi.org/10.1007/s10750-016-2910-8
Gherardi F (2007) Biological invaders in inland waters: profiles, distribution and threats. Springer, Dordrecht, The Netherlands, 734 pp, https://doi.org/10.1007/978-1-4020-6029-8
Hall RO Jr, Tank JL, Dybdahl MF (2003) Exotic snails dominate nitrogen and carbon cycling in a highly productive stream. *Frontiers in Ecology and the Environment* 1: 407–411, https://doi.org/10.2307/3868137
Havel JE, Kovalenko KE, Thomza SM, Amalfitan S, Kats LB (2015) Aquatic invasive species: challenges for the future. *Hydrobiologia* 750: 147–170, https://doi.org/10.1007/s10750-014-2166-0
Hechinger RF (2012) Faunal survey and identification key for the trematodes (Platyhelminthes: Digenea) infecting *Potamopyrgus antipodarum* (Gastropoda: Hydrobiidae) as first intermediate host. *Zootaxa* 3418: 1–27
Higgins SN, Vander Zanden MJ (2010) What a difference a species makes: a meta-analysis of dreissenid mussel impacts on freshwater ecosystems. *Ecological Monographs* 80: 179–196, https://doi.org/10.1890/09-1249.1

Ibáñez M, Alonso MR (1977) Geographical distribution of *Potamopyrgus jenkinsi* (Smith 1889) (Prosobranchia: Hydrobiidae) in Spain. *Journal of Conchology* 29: 141–146

Johnson PTJ, Olden JD, Vander Zanden MJ (2008) Dam invaders: impoundments facilitate biological invasions into freshwaters. *Frontiers in Ecology and the Environment* 6: 359–365, https://doi.org/10.1890/070156

Kaplan H, van Niekerk A, Le Roux JJ, Richardson DM, Wilson JRU (2014) Incorporating risk mapping at multiple spatial scales into eradication management plans. *Biological Invasions* 16: 691–703, https://doi.org/10.1007/s10530-013-0611-z

Karatayev AY, Burlakova LE, Padilla DK, Mastitsky SE, Olenin S (2009) Invaders are not a random selection of species. *Biological Invasions* 11: 2009–2019, https://doi.org/10.1007/s10530-009-9498-0

LeClair LL, Cheng YW (2011) A review of salinity tolerances for the New Zealand mudsnail (*Potamopyrgus antipodarum*, Gray 1843) and the effect of a controlled saltwater backflush on their survival in an impounded freshwater lake. *Journal of Shellfish Research* 30: 905–914, https://doi.org/10.2983/035.030.0332

Liang L, Clark JT, Kong N, Rieske LK, Fei S (2014) Spatial analysis facilitates invasive species risk assessment. *Forest Ecology and Management* 315: 22–29, https://doi.org/10.1016/j.foreco.2013.12.019

Lindim C (2015) Modeling the impact of Zebra mussels (*Dreissena polymorpha*) on phytoplankton and nutrients in a lowland river. *Ecological Modelling* 301: 17–26, https://doi.org/10.1016/j.ecolmodel.2015.01.012

Lodge DM, Stein RA, Brown KM, Covich AP, Bronmark C, Garvey JE, Klosiewski SP (1998) Predicting impact of freshwater exotic species on native biodiversity: challenges in spatial scaling. *Australian Journal of Ecology* 23: 53–67, https://doi.org/10.1111/j.1442-9993.1998.tb00705.x

Lodge DM, Williams S, MacIsaac HJ, Hayes KR, Leung B, Reichard S, Mack RN, Moyle PB, Smith M, Andow DA, Carlton JT, McMichael A (2006) Biological invasions: recommendations for U.S. policy and management. *Ecological Applications* 16: 2035–2054, https://doi.org/10.1890/1051-0761(2006)016[2035:BIRFUP]2.0.CO;2

Lorenzo-Lacruz J, Vicente-Serrano SM, Lopez-Moreno JI, Moran-Tejeda E, Zabalza J (2012) Recent trends in Iberian streamflows (1945-2005). *Journal of Hydrology* 414: 463–475, https://doi.org/10.1016/j.jhydrol.2011.11.023

Lowe S, Browne M, Boudjelas S, De Poorter M (2000) 100 of the world's worst invasive alien species a selection from the global invasive species database. Published by the Invasive Species Specialist Group (ISSG) a specialist group of the Species Survival Commission (SSC) of the world conservation union (IUCN), p 12. First published as special lift-out in Aliens Dec 12th 2000. (Updated and reprinted version)

Martínez-Ortí A, Aparicio MT, Robles F (2004) The molluscan fauna of the Alcaraz mountains (Albacete, Spain). *Iberus* 22: 9–17

Matsuzaki SS, Usio N, Takamura N, Washitani I (2009) Contrasting impacts of invasive engineers on freshwater ecosystems: an experiment and meta-analysis. *Oecologia* 158: 673–686, https://doi.org/10.1007/s00442-008-1180-1

Mazza G, Agostini N, Aquiloni L, Cienfanelli S, Tricarico E, Gherardi F (2011) Ecological characterisation of streams invaded by the New Zealand mud snail *Potamopyrgus antipodarum* (Gray 1843): the case study of a National Park in Italy. *Ethology, Ecology & Evolution* 23: 151–164, https://doi.org/10.1080/03949370.2011.555084

McMillin S, Trumbo J (2009) Field assessment of bayluscide treatments for the control on New Zealand mudsnail *Potamopyrgus antipodarum* in a concrete-lined canal. *California Fish and Game* 95: 147–152

Moore JW, Herbst DB, Heady WN, Carlson SM (2012) Stream community and ecosystem responses to the boom and bust of an invading snail. *Biological Invasions* 14: 2435–2446, https://doi.org/10.1007/s10530-012-0240-y

Moorhouse TP, Macdonald DW (2015) Are invasives worse in freshwater than terrestrial ecosystems? *Wiley Interdisciplinary Reviews-Water* 2: 1–8, https://doi.org/10.1002/wat2.1059

Mouthon J, Charvet S (1999) Compared sensitivity of species, genera and families of Molluscs to biodegradable pollution. *Annales de Limnologie-International Journal of Limnology* 35: 31–39, https://doi.org/10.1051/limn/1999009

Olson ER, Ventura SJ, Zedler JB (2012) Merging geospatial and field data to predict the distribution and abundance of an exotic macrophyte in a large Wisconsin reservoir. *Aquatic Botany* 96: 31–41, https://doi.org/10.1016/j.aquabot.2011.09.007

Orozco A, Cadevll J, Bros V, Hernández E, Nebot J, Uribe F (2001) Inventory of fresh-water Mollusca of la Ricarda-ca l`Arana (Llbregat Delta). *Bulletí Naturalista del Delta del Llobregat* 4: 1–18

Pérez-Murciano S, Andreu-Moliner E, de Pauw N (1998) Estudio de las comunidades de macroinvertebrados de la Cuenca alta del río Turia (Teruel, España). *Ecología* 12: 175–186

Petsch DK (2016) Causes and consequences of biotic homogenization in freshwater ecosystems. *International Review of Hydrobiology* 101: 113–122, https://doi.org/10.1002/iroh.201601850

Pérez-Bilbao A, Calapez AR, Feio MJ (2014) Aquatic Coleoptera distribution patters and their environmental drivers in central Portugal, Iberian Peninsula. *Limnologica* 46: 45–57, https://doi.org/10.1016/j.limno.2013.12.006
Pérez-Tris J, Santos T (2004) Spanish research on avian migration: historical trajectory and future perspectives. *Ardeola* 51: 71–89
Pigneur LM, Falisse E, Roland K, Everbecq E, Deliege JF, Smitz JS, van Doninck K, Descy JP (2014) Impact of invasive Asian clams, *Corbicula* spp., on a large river ecosystem. *Freshwater Biology* 59: 573–583, https://doi.org/10.1111/fwb.12286
Prenter J, MacNeil C, Dick JTA, Dunn AM (2004) Roles of parasites in animal invasions. *Trends in Ecology and Evolution* 19: 385–390, https://doi.org/10.1016/j.tree.2004.05.002
Riley LA, Dybdahl MF, Hall RO (2008) Invasive species impact: asymmetric interactions between invasive and endemic freshwater snails. *Journal of the North American Benthological Society* 27: 509–520, https://doi.org/10.1899/07-119.1
Rolán E (2004) Sobre una peculiar población de *Potamopyrgus antipodarum* en el tramo final del río Miño. *Noticiario de la Sociedad Española de Malacología* 42: 50–53
Rosenberg DM, Resh VH (1993) Introduction to freshwater biomonitoring and benthic macroinvertebrates. In: Rosenberg DM, Resh VH (eds), Freshwater Biomonitoring and Benthic Macroinvertebrates. Chapman and Hall, New York, pp 1–9
Schreiber ESG, Lake PS, Quinn GP (2002) Facilitation of native stream fauna by an invading species? Experimental investigations of the interaction of the snail, *Potamopyrgus antipodarum* (Hydrobiidae) with native benthic fauna. *Biological Invasions* 4: 317–325, https://doi.org/10.1023/A:1020925022843
Serrano L, Reina M, Arechederra A, Casco MA, Toja J (2004) Limnological description of the Tarelo lagoon (SW Spain). *Limnetica* 23: 1–10
Simoes M (1988) Distribución en Portugal de *Potamopyrgus jenkinsi* (Prosobranchia Hydrobiidae). *Iberus* 8: 243–244
Sousa R, Antunes C, Guilhermino L (2008) Ecology of the invasive Asian clam *Corbicula fluminea* (Müller, 1774) in aquatic ecosystems: an overview. *International Journal of Limnology* 44: 85–94, https://doi.org/10.1051/limn:2008017
Stockton-Fiti KA, Moffitt CM (2017) Safety and efficacy of Virkon® aquatic as a control tool for invasive molluscs in aquaculture. *Aquaculture* 480: 71–76, https://doi.org/10.1016/j.aquaculture.2017.08.005
Strayer DL (1999) Effects of alien species on freshwater mollusks in North America. *Journal of the North American Benthological Society* 18: 74–98, https://doi.org/10.2307/1468010
van Leeuwen CHA, van der Velde G (2012) Prerequisites for flying snails: external transport potential of aquatic snails by waterbirds. *Freshwater Science* 31: 963–972, https://doi.org/10.1899/12-023.1
van Leeuwen CHA, van der Velde G, van Groenendael JM, Klaassen M (2012) Gut travellers: internal dispersal of aquatic organisms by waterfowl. *Journal of Biogeography* 39: 2031–2040, https://doi.org/10.1111/jbi.12004
Vidal-Abarca MR, Suarez ML (2013) Which are, what is their status and what can we expect from ecosystem services provided by Spanish rivers and riparian areas? *Biodiversity Conservation* 22: 2469–2503, https://doi.org/10.1007/s10531-013-0532-2
Vinson MR, Baker MA (2008) Poor growth of rainbow trout fed New Zealand mud snails *Potamopyrgus antipodarum*. *North American Journal of Fish Management* 28: 701–709, https://doi.org/10.1577/M06-039.1
Wilke T, Haase M, Hershler R, Liu H-P, Misof B, Ponder W (2013) Pushing short DNA fragments to the limit: phylogenetic relationships of 'hydrobioid' gastropods (Caenogastropoda: Rissooidea). *Molecular Phylogenetics and Evolution* 66: 715–736, https://doi.org/10.1016/j.ympev.2012.10.025
Winterbourn M (1970) The New Zealand species of *Potamopyrgus* (Gastropoda: Hydrobiidae). *Malacologia* 10: 283–321
Zbikowski J, Zbikowska EE (2009) Invaders of an invader – Trematodes in *Potamopyrgus antipodarum* in Poland. *Journal of Invertebrate Pathology* 101: 67–70, https://doi.org/10.1016/j.jip.2009.02.005

Supplementary material

The following supplementary material is available for this article:

Table S1. The geo-referenced records of *Potamopyrgus antipodarum* in the Iberian Peninsula.

This material is available as part of online article from:
http://www.reabic.net/journals/bir/2019/Supplements/BIR_2019_Alonso_etal_Table_S1.xlsx