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Research Article

Occurrence of the freshwater invasive snail *Potamopyrgus antipodarum* in Madeira Island (Portugal): distribution and impacts on benthic communities

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Abstract

Potamopyrgus antipodarum (Gray, 1843) has been considered one of the most successful and widespread invasive freshwater molluscs worldwide. This snail has been present in mainland Portugal since the 1960s, but there is only scarce information regarding its presence in Madeira or Azores archipelagos. In this work, macroinvertebrate communities were sampled in six Madeira Island streams. *P. antipodarum* was found in all sampled sites, with abundances ranging from 3 to 3528 individuals per sampling area, indicating that the species arrived at Madeira recently and is now in a clear spreading phase. Our results indicate no relationship between the abundance of *P. antipodarum* and macroinvertebrates' biodiversity indices. Nevertheless, the abundance of *P. antipodarum* was extremely high in some locations, representing more than 30% of all benthic invertebrates, which triggered alterations in the food web and community structure. The future impacts of this invasion are for now unpredictable, but given *P. antipodarum* parthenogenetic reproduction and fast spread, its presence can potentially affect Madeira Island's aquatic ecosystems' ecological status and services. These results can inform environmental agencies on the importance of monitoring the presence and spread of this invasive species and call for management strategies focused on early detection and control measures. Given the endemicity and insularity of Madeira macroinvertebrate communities, the spread of *P. antipodarum* should be limited to mitigate its ecological impacts and biodiversity loss.

Key words: Freshwater macroinvertebrates, Invasion ecology, Island ecosystems, New Zealand mud snail

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Introduction

Invasive species are a significant component of human-caused global environmental change (Brook et al. 2008), and freshwater invasions are of particular concern since freshwater ecosystems are among the most diverse and endangered in the world

(Dudgeon and Strayer 2024). Alien invasive species are a major driving force behind species extinctions (Pyšek et al. 2020) and a major threat to ecosystem services, biodiversity and genetic diversity of native species (Higgins and Zanden 2010). Becoming invasive is a complex process, and the impacts of alien species on native communities will depend on the characteristics of the invaded community and environmental conditions (Gherardi 2007). As climatic, hydrological, and other environmental conditions will vary across regions, the success and impacts of potentially invasive species are also likely to diverge across regions (Alonso and Castro-Díez 2008). Moreover, global trading and transport have led to a collapse of biogeographical barriers, and human-aided transport has increased the frequency of introduction events of alien species without precedent (Capinha et al. 2017; Moser et al. 2018; Pyšek et al. 2010). In islands, given their isolation, fewer intentional and accidental alien arrivals (i.e., lower number of arriving and colonization pressures) are to be expected and consequently, lower colonization rates are usually registered. Nevertheless, human activities drastically changed the invasive patterns and the invasion rate in island ecosystems. The number of arrivals is now dependent more on the size of the island economy than on the distance to mainland (Deidda 2016; Russell and Kueffer 2019). Also, isolated island native species usually exhibit reduced phylogenetic diversity, which can make them more vulnerable to biological invasion (Weigelt et al. 2015). Consequently, geographical isolation of remote oceanic islands can often increase the successful establishment of alien species and the impacts caused by the colonization of alien species in island ecosystems (Fridley and Sax 2014; Moser et al. 2018).

The New Zealand mud snail, *Potamopyrgus antipodarum* (Gray, 1843) (hereafter NZMS), is an ovoviviparous and parthenogenic freshwater Tateidae snail native to New Zealand (Alonso et al. 2019). NZMS is primarily a scraper/grazer species that feeds mostly on diatoms, but also organic detritus and macrophytes (James et al. 2000). NZMS possesses internal gills for aquatic respiration and an operculum to seal itself tightly into the shell (Richards et al. 2001). This snail species can survive unfavorable conditions such as high salinity levels, desiccation, temperature variations and predation, including surviving many fishes' digestive systems (Bennett et al. 2015; Haynes et al. 1985). This species also exhibits a high capacity to establish itself in human-altered water bodies and streams that experience continuous pressure from anthropogenic activities (Vermonden et al. 2010; Spyra et al. 2015). Invasive populations of NZMS are composed entirely of parthenogenetic females (Butkus et al. 2012), allowing the species to colonize rapidly and extend to new ecological niches (Poirier 2013), reaching incredibly high densities (more than 500 000 individuals per m^2) (Hall et al. 2006).

In the last century, NZMS has invaded temperate and subtropical aquatic ecosystems worldwide (Ponder 1988; Naser and Son 2009; Collado 2014; Taybi et al. 2021; Geist et al. 2022). The presence of NZMS in mainland Portugal has been reported since 1960 (Heuss 1961). Still, there is limited information on Portuguese island ecosystems: in Madeira Island, the species was recently reported (Órfão et al. 2024), and in the Azores archipelago, its presence was not yet confirmed. Faunal surveys and monitoring programs conducted on Madeira until 2015 did not find evidence of the occurrence of NZMS (Hughes 2003; Borges et al. 2008; Raposeiro et al. 2009; Raposeiro et al. 2022) suggesting a recent invasion whose impacts on native communities remain unknown.

As in other oceanic islands, species richness in Madeira's streams is low, in comparison with mainland lotic ecosystems (Malmqvist 1988; Raposeiro et al. 2012). Freshwater benthic invertebrate communities are characterized by low diversity, with some taxonomic groups absent (e.g., Plecoptera and Amphipoda) (Raposeiro et al. 2022) and many families are usually represented by few genera with a few or even single species (Stauder 1991). Insect orders dominate benthic communities,

particularly Diptera (Hughes 2005) and non-insect orders are poorly represented and tend to be introduced by more passive dispersal methods such as attachment to birds or ships (Zaranko et al. 1997; Hughes 2005). On the other hand, Madeira Island freshwater habitats harbour many endemic taxa (circa 30% of the species, including Trichoptera, Coleoptera, *Hydracarina* and some Dipteran families), most of them being restricted to areas of indigenous vegetation located in the upper part of the rivers (>500 m above sea level) (Hughes et al. 1998; Hughes 2003). Generally, island native communities around the globe are suffering significant negative impacts caused by invasive species, primarily leading to the loss of biodiversity but also impacting community composition and ecosystem services (Russell et al. 2017).

Given the invasive potential of NZMS and the inherent conservation importance of Madeira's freshwaters, the aim of this study was to investigate the distribution and possible impacts of this invasive snail species by correlating its occurrence with macroinvertebrate native community composition and structure.

Methods

Study area

The Madeira archipelago is part of the Macaronesia islands, and it is a Portuguese territory (Figure 1). It is in the Atlantic Ocean, Southwest of the Iberian Peninsula, between latitudes 32°24' and 33°07'N and longitudes 16°16' and 17°16'W and it has an area of 736,75 km^2 (Raposeiro et al. 2022). The distance between this archipelago and Portugal is about 1,000 km, and between the archipelago and the closest point of the Western African coast is approximately 600 km (Glauser 2020). Madeira Island has a moist temperate climate with moderate winters, including two main types: Mediterranean and temperate climates (Borges et al. 2008). Madeira Island presents a dense hydrographic system comprising approximately 126 catchments and 200 streams (Marques 1994). Macaronesian watersheds exhibit a predominantly radial drainage pattern as streams flow away from the central peaks (Prada et al. 2005). The streams of Madeira Island have a short and narrow profile, crossing steep valleys, often characterized by turbulent, torrential and seasonal flows (Hughes 2003; Prada et al. 2005). The upper and middle forest courses of Macaronesian rivers correspond to leaf-litter-dominated continental headwater systems, while the lower river courses correspond to algal-producing basins (Hughes 2005). Substrates are coarse, comprising bedrock, rolled boulders, a mixture of cobbles and pebbles, sand and gravel (Glauser 2020; Raposeiro et al. 2022). Due to the complex orography of the island, vegetation and land use are distributed along an altitudinal gradient. Madeira's lower altitudes are characterized by urban and agricultural land uses, while exotic forest plantations are at mid-altitudes (Raposeiro et al. 2022). The native forest and less impacted areas occupy the upper, higher altitude parts of the island (Raposeiro et al. 2022). Macaronesian freshwater ecosystems are particularly vulnerable to anthropogenic and environmental stressors, given the inherently fragile nature of insular ecosystems, coupled with their exceptional conservation value, given the high number of endemic aquatic species present (Hughes 2005; Glauser 2020). Besides that, due to the increasing anthropogenic pressures, namely urbanization, deforestation and destruction of the riparian vegetation, Madeira's freshwater systems are suffering environmental degradation (Hughes 2005; Borges et al. 2008; Glauser 2020). In addition, on Madeira Island, Laurisilva forests are vital for the hydrological cycle and crucial for the protection of freshwater habitats (Hughes 2005). Therefore, water abstraction used for agriculture and hydroelectric production (Prada et al. 2005), together with climatic changes and a decrease in rainfall (Hughes 2005), put these freshwaters under additional stress.

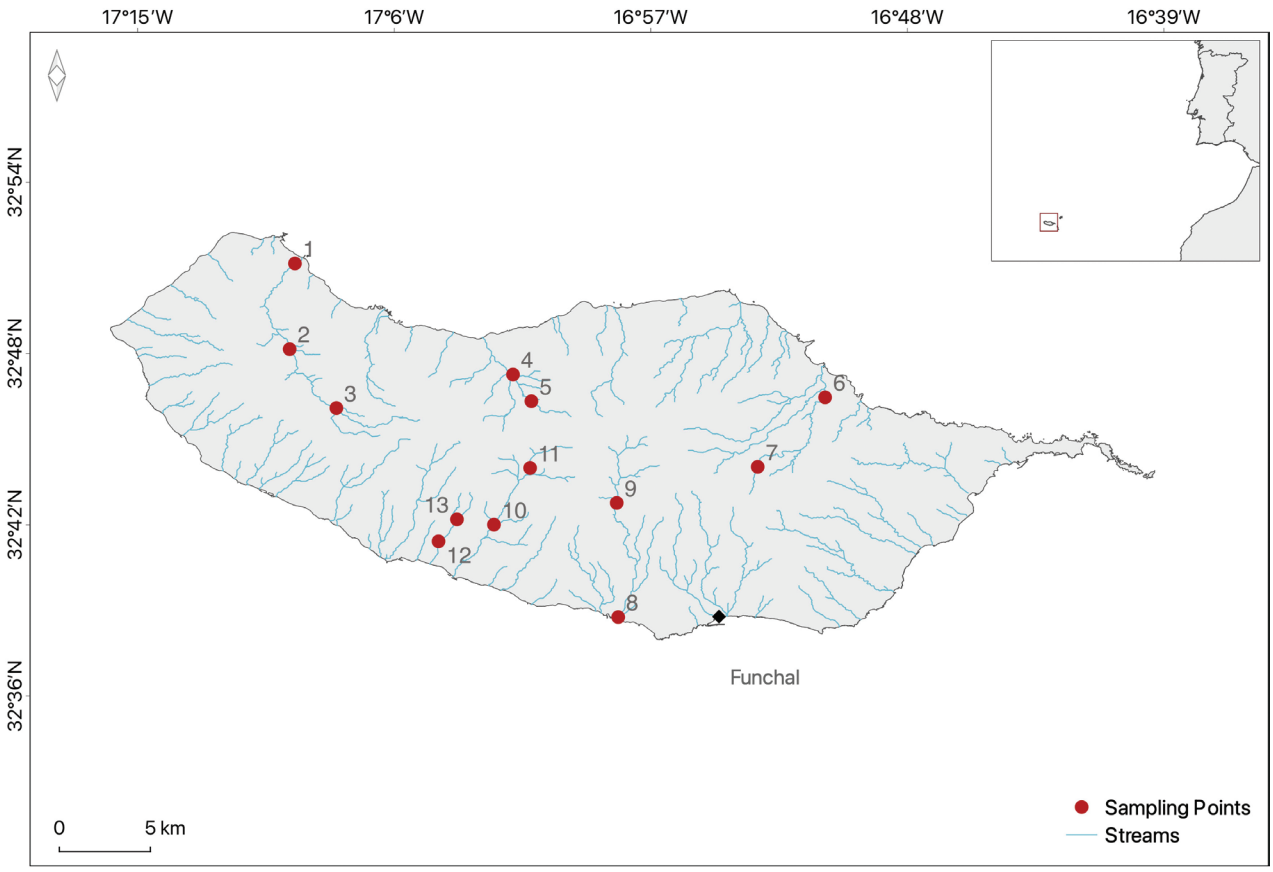

Figure 1. Map of Madeira Island with 13 sampling sites from 6 streams: 1- Ribeira da Janela (downstream), 2- Ribeira da Janela (middle stream), 3 – Ribeira da Janela (upstream), 4 – Ribeira de São Vicente (downstream), 5 – Ribeira de São Vicente (upstream); 6 – Ribeira do Faial (downstream), 7 – Ribeira do Faial (upstream), 8 – Ribeira dos Socorridos (downstream), 9 – Ribeira dos Socorridos (upstream), 10 – Ribeira Brava (downstream), 11 – Ribeira Brava (upstream), 12 – Ribeira da Tábua (downstream), 13 – Ribeira da Tábua (upstream).

Sampling procedure

We selected 13 sampling points in 6 permanent streams of Madeira Island, based on established periodic monitoring programs. The sites were chosen to cover the range of natural variation and human disturbance. Sampled streams are Socorridos, Brava, São Vicente, Tábua, Faial, and Janela streams (Figure 1). Brava downstream, Socorridos downstream and Tábua downstream are urban sites; São Vicente upstream and downstream, Socorridos upstream, Tábua downstream and Janela downstream are rural sites; Brava upstream, Faial upstream and downstream, and Janela middle stream and upstream are forest sites.

Using the Portuguese official protocol for the collection of benthic macroinvertebrates (INAG 2008), we employed a semiquantitative kick and sweep (K&S) technique to collect the entire benthic macroinvertebrate community in each sampling point, during the Spring of 2022. We performed this technique along 50 meters of stream extension, using a standard hand net with a 25 × 50 cm area with a 500 µm mesh size. In the selected section of the stream, we collected 6 transects, each 1 meter long by 0.25 meters wide, to produce one sample that covered the different existing microhabitats. The sampling material was stored in plastic pots and conserved in Ethanol 70%. Macroinvertebrates were later counted and identified to the lowest taxonomic level possible (Tachet et al. 2000; Prat and Rieradevall 2014) using Zeiss Stemi 508 stereomicroscope.

Data analysis

For each sampling site, the macroinvertebrate community was characterized using common descriptors such as species richness, abundance, species diversity (Shannon-Wiener's index), specific dominance (Simpson's index), species evenness (Pielou's index), and Ephemeroptera, Plecoptera, and Trichoptera relative frequency (% EPT). In addition, the Madeiran Biotic Score II (MBS II index) was calculated to assess the ecological status of the streams. MBS II is an exclusive index created for Madeira Island, based on the composition of benthic macroinvertebrate assemblages; it uses a scoring system of 38 indicator taxa, where negative scores are assigned to taxa increasingly tolerant to pollution (mainly organic), while the highest scoring taxa are pollution intolerant. After the calculation of the index, a given river/stream is then classified as "Bad," "Poor," "Fair," or "Good" based on the amount of positive/negative indicator organisms (Hughes 2003).

Logarithmically transformed abundances of NZMS were analyzed in a correlation-focused analysis relative to abiotic parameters, community descriptors and biotic indexes, using Pearson correlation. The statistical analyses and graphics were performed using GraphPad Prism software (version 9.0.0).

Results

The streams sampled were characterized by low and medium water velocities, low depth (between less than 0.25 and 0.5 meters), temperature varying between 13 and 21 °C, conductivity ranging between 63 and 226 µs/cm, dissolved oxygen between 7.5 and 10 mg/L O_2 and pH between 7.2 and 8.2 (Suppl. material 1: table S1). NZMS was found in all streams and in 9 of the 13 sampling sites, namely in Socorridos upstream, Brava upstream and downstream, São Vicente downstream, Tábua upstream and downstream, Faial downstream and Janela midstream and upstream. The abundance of NZMS per stream ranged from 3 to 3528 organisms per sample (Table 1). No relationship was found between the abundance of NZMS and the measured abiotic parameters (temperature, dissolved oxygen, conductivity or pH, Suppl. material 1: fig. S1).

Looking at community descriptors of all sampled streams, Community Richness ranged between 11 and 21 taxa; Abundance in each sampled area ranged between 202 and 6295 organisms; Shannon-Wiener's diversity ranged between 0.82 and 1.64 (Table 1); Pielou's species evenness index ranged between 0.29 and 0.61; and Simpson's specific dominance index ranged between 0.39 and 0.73 (Suppl. material 1: table S2). The correlation between NZMS abundance and species richness showed an unexpected and moderate positive correlation, showing that where biodiversity is greatest is where NZMS abundance is higher (R^2 = 0.36; Figure 2a). Regarding the other community descriptors, no correlation was found between the abundance of NZMS and Shannon-Wienner diversity index (R^2 = 0.11), Simpson's diversity (R^2 = 0.09) and Pielou's species evenness (R^2 = 0,009), showing that the structure of the macroinvertebrate communities was not explained by variation in NZMS abundance values (Figure 2). Regarding the percentage of EPT *taxa* in the benthic communities, it was very low in all sampled sites, as expected, ranging between 0,08 and 0,78%. No correlation with the abundance of NZMS was found (R^2 = 0,026, Figure 3).

According to the MBS II index, the biotic index for Madeira Island, we observed that the sampled streams of Madeira Island varied between sites classified as Poor and Good. Streams of good quality typically were found

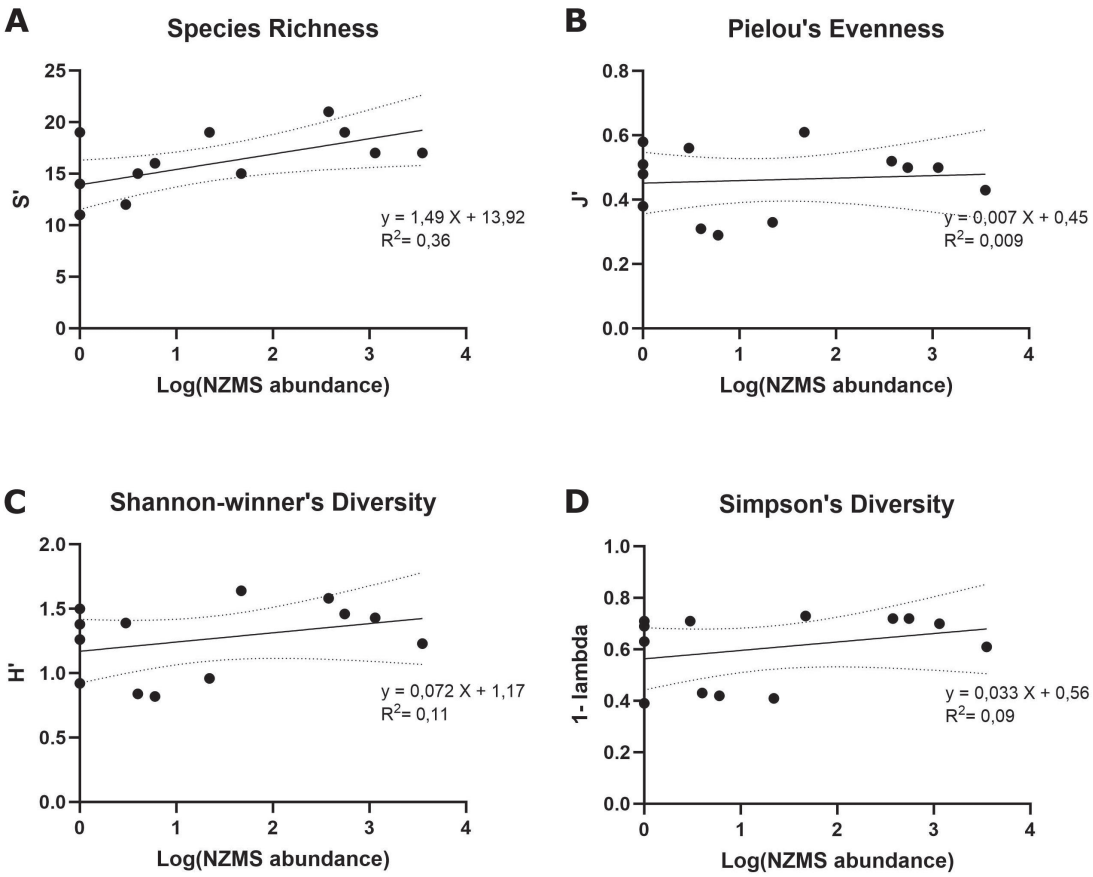

Figure 2. Pearson Correlation between NZMS abundance and community descriptors: Species richness (**a**), Pielou's evenness (**b**), Shannon-Winner diversity index (**c**) and Simpson's diversity index (**d**). NZMS abundances went through a logarithmic transformation. 95% confidence bands of the best-fit line are represented with dashed lines.

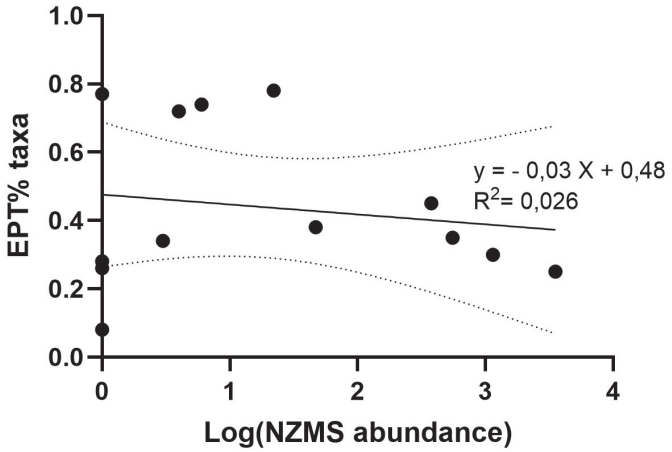

Figure 3. Pearson Correlation between the NZMS abundance and the ratio of EPT *taxa* in the community. NZMS abundances went through a logarithmic transformation. 95% confidence bands of the best-fit line are represented with dashed lines.

in forested areas, while streams of poor quality are mainly associated with urban and rural areas where human activity is more prevalent (see Table 1). No correlation was found between the NZMS abundances and the Madeira biotic index, meaning that the presence of the invasive species seems to be independent of the stream's ecological status (Figure 4). Regarding feeding

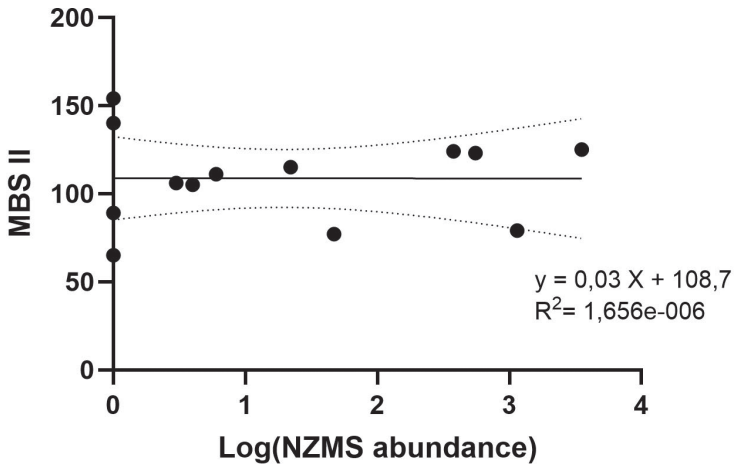

Figure 4. Pearson Correlation NZMS abundance and MBS II index (Madeiran Biotic Score II). NZMS abundances went through a logarithmic transformation. 95% confidence bands of the best-fit line are represented with dashed lines.

Table 1. Characterization of the sampling sites. N: macroinvertebrate abundance (excluding NZMS); H': Shannon-Wiener's diversity index; MBS II: Madeiran Biotic Score II; Classification (according to MBSII): Poor (Yellow, > 35 - < 91), Fair (Green, > 91 - < 120) and Good (Blue, > 120). Sampling sites are organized by a gradient of NZMS abundance; D (downstream) U (upstream) and I (midstream) indicate the sampling position on the stream.

Sampling site	Land use	N	NZMS abundance	H'	MBS II	Classification
Janela U	Forest	493	0	1,5	154	Good
Faial U	Forest	2427	0	1,26	140	Good
S. Vicente U	Rural	1143	0	1,38	89	Poor
Socorridos D	Urban	202	0	0,92	65	Poor
Socorridos U	Rural	421	3	1,39	106	Fair
S. Vicente D	Rural	1901	4	0,84	105	Fair
Janela D	Rural	3950	6	0,82	111	Fair
Tábua D	Urban	1547	22	0,96	115	Fair
Brava D	Urban	408	47	1,64	77	Poor
Faial D	Forest	1308	377	1,58	124	Good
Brava U	Forest	1226	553	1,46	123	Good
Tábua D	Rural	1596	1144	1,43	79	Poor
Janela I	Forest	2767	3528	1,23	125	Good

modalities, Madeira macroinvertebrate communities are characterized by being almost entirely composed of filterer and scraper/grazer species, with a low number of predators, fine sediment feeders/collectors and shredders (Suppl. material 1: table S3). As the abundance of NZMS (that presents a predominantly grazer feeding behavior) increases in a community, the relative abundances of other scrapers/grazers and filter feeders decrease. In sampling sites without or with low abundance of NZMS other grazers constituted, on average, around 60% of the total abundance, while in communities where NZMS was abundant, the ratio of scrapers/grazers dropped to less than 50%. For instance, at Tábua downstream and Janela midstream, where the highest abundance of NZMS was recorded, the percentage of other grazers was only 33 and 28%, respectively (Figure 5).

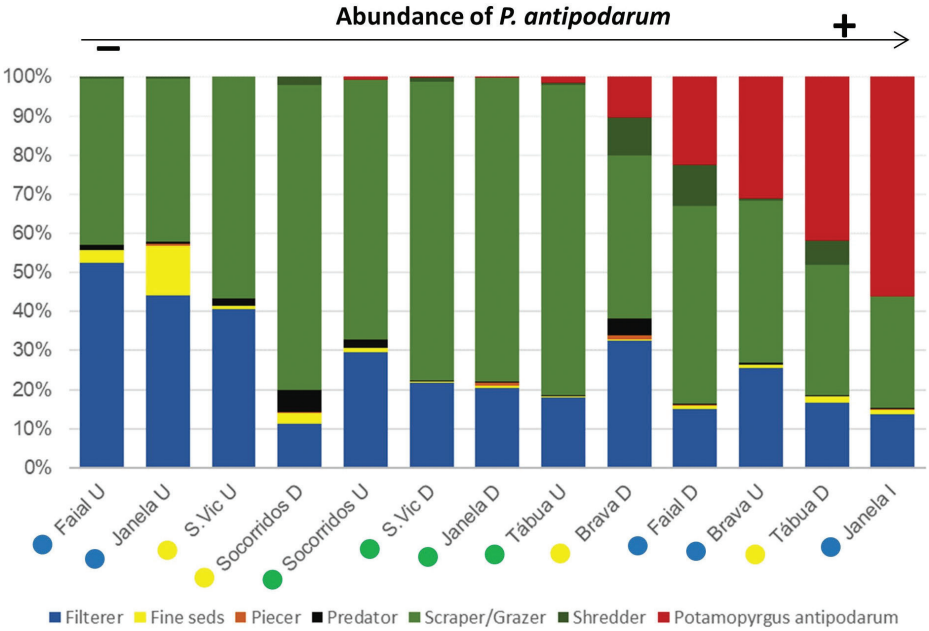

Figure 5. Graphical representation of the percentage of macroinvertebrate feeding group modalities (shredder, scraper/grazer, predator, piecer, fine sediments, filterer) for all sampling sites. Sites are ordered from left to right by the abundance of NZMS. The circles next to the streams names indicates Madeiran Biotic Score II classification: Poor (yellow), Fair (green), Good (blue).

Discussion

The current study revealed the occurrence of the highly invasive New Zealand mud snail in different catchments in Madeira Island. Freshwater alien snail species are often introduced inadvertently by fish-farming and commercial trade of aquaculture products, attached to fish or aquatic plants, or because of human and cargo transportation, for example, within ballast waters (Zaranko et al. 1997; Cowie 2000). According to Raposeiro (2022) NZMS was not present in Madeira Island until 2015, and the first records of the species date from 2017 (Órfão et al. 2024). Our results thus show that within the last seven years NZMS has become common in freshwater systems across the island, and illustrate the incredible invasive potential of this species, supported by its fast and asexual reproduction, broad diet and lack of predators on the island. According to Órfão et al. (2024), NZMS arrival may be related to the introduction of Rainbow trout (*Oncorhynchus mykiss*) in Madeira for recreational fishing purposes. Previous data supports the hypothesis of the Rainbow trout as a vector since it can transport alive snails in its digestive tract (Vinson and Baker 2008). Nevertheless, further investigation is needed to clarify the origin of the invasion. Like most invasive species, NZMS can probably be accidentally transported between basins within the island through natural vectors, such as birds, or by human activities, such as hiking or canyoning.

The abundance of NZMS in Madeira streams is not related to any of the measured abiotic parameters (temperature, dissolved oxygen, conductivity or pH), which contrasts with previous findings for this species. Research indicates that low conductivity levels can limit the growth and survival of NZMS (Herbst et al. 2008; Larson et al. 2020). Additionally, field studies suggest that NZMS is more likely to occur in water bodies with low velocity and pH levels, along with high conductivity (Spyra et al. 2015; Larson et al. 2023). Also NZMS showed no preference for specific sections of the stream and it was found at both upstream and downstream sections. NZMS may establish itself in the upper portion of streams, mainly by spreading through vegetation and edges of the faster-flowing waters and then moving into new habitats,

particularly unoccupied vegetation habitats (Richards et al. 2001). The dispersion along streams shows that, despite the recent invasion, NZMS is already in a spreading phase. Given its high fecundity and generalist food and habitat requirements, NZMS can achieve extremely high densities in invaded ecosystems and out-compete native species (Kerans et al. 2005; Hall et al. 2006; Riley et al. 2008). Nevertheless, given the short time since the arrival of NZMS on Madeira Island, significant impacts were not expected. Our study found no correlation between the abundance of NZMS and most community descriptors. Instead, native communities' richness and diversity are related to the ecological status of streams and not to the presence of invasive species (Borges et al. 2008). Also, riparian vegetation and land use adjacent to the streams varied among the different sampling sites: sites with viniculture, or areas susceptible to urban and agricultural runoff showed lower scores on the regional ecology status index and less biodiversity (Hughes and Furse 2001; Hughes 2005). The absence of a relationship between the number of EPT taxa and the abundance of NZMS indicates that there is currently no evidence suggesting that the invasion is impacting the most sensitive species. For instance, Kerans et al. (2005) found a negative correlation between the densities of NZMS and the densities of taxa competing with the snails for food and/or space such as Ephemerellidae and Brachycentridae. Thus, further studies are needed to ascertain the effects of the mud snails on native EPT species such as the mayfly nymphs *Baetis* sp. or caddisfly larvae such as *Tinodes* sp. or the endemic *Hydropshyche maderensis*. Capinha et al. (2020) noted that the presence of exotic species on islands has a stronger influence on community composition than on species richness. The presence of exotic species often increases the number of species locally but also increases homogenization of macroinvertebrate communities due to better dispersion ability of invasive taxa. This trend may predict future changes in Madeiran macroinvertebrate communities, and it is already possible to observe the absence of some Trichoptera species, such as *Tinodes* or *Polycentropus* species, in catchments with NZMS. Madeira macroinvertebrate community composition and structure should, therefore, be carefully monitored to determine whether there is a temporal trend towards homogenization.

Regarding feeding group diversity, some differences between heavily invaded and non-invaded sites were recorded. In the highly invaded sites, the proportion between the different feeding groups was altered by the presence of NZMS, especially the significant reduction of the relative abundance of native grazers and filter feeders. Previous studies already demonstrated that NZMS can compete with other grazer species for resources, reducing the biomass of food available for other herbivores (Riley et al. 2008; Moore et al. 2012). In Ribeira da Janela (intermediate), the sampling site where the highest abundance of NZMS was recorded, other detritivores species (such as *Asellus* sp., relatively common in other sampling sites) are completely absent, suggesting that competition with these species may also be occurring. These results show that changes in the community structure may be happening due to NZMS presence, which can lead to effects for insular freshwater food webs and ecosystem functions. Given the natural low diversity and abundance of Madeira's benthic macroinvertebrates, the presence and spread of NZMS over time could lead to a decline of the functional integrity of the invaded ecosystems, leading to habitat degradation or modification (Arango et al. 2009; Hall et al. 2006). The alteration of food webs by the presence of NZMS has already been described by several authors, showing that the species can consume most of the primary production, heavily influencing nutrient fluxes (Arango et al. 2009; Hall et al. 2006). The depletion of native grazers can also lead to imbalances in the concentration and distribution of phytoplankton and alterations in periphyton community structure and biomass (Bennett et al. 2015; Grant et al.

2008). NZMS, when present in high densities, can alter algae communities, reducing the abundances of medium-sized and large diatoms and several filamentous cyanobacteria and chlorophytes, thus increasing the relative abundances of tough filamentous chlorophytes (Krist and Charles 2012; Bennett et al. 2015).

The biodiversity crisis is nowhere more evident and demanding of attention than on island ecosystems (Djamali 2013). Recent studies show that around 73% of threatened species on the IUCN Red List found only on islands are being threatened by invasive species (Russell and Kueffer 2019). Madeira Island is no exception since endemic species are usually limited to restricted habitats and are often already under serious threat due to agropastoral activities, urbanization, and biological invasions (Hughes 2003). The total number of invasive species on Madeira is nearly 400 (Região Autónoma da Madeira - Assembleia Legislativa 2023), while endemic species and subspecies from the Madeira archipelago are about 1,419 (1,286 species and 182 subspecies), representing 19% of the overall species richness (Borges et al. 2008). Invertebrates are the most diverse group within endemic *taxa* (210 Mollusca and 979 Arthropoda) with 71% of all mollusks endemic (Borges et al. 2008). The Laurisilva forest within Madeira Natural Park is an outstanding relict of a previously widespread laurel forest. It is the largest area of laurel forest, with an estimated 90% primary forest containing a unique suite of plants and animals, including a high proportion of endemic species (UNESCO 2009). Janela Stream is the main watercourse within the protected area harboring Laurisilva forest, but it was also the stream where the highest NZMS abundance was recorded. Given the importance of the area for conservation and its inherent fragility, this location is of concern and where significant impacts can be expected. To better monitor and evaluate possible impacts of the invasion by NZMS, it would be advisable to assess its influence on ecosystem functions, such as primary production and organic matter degradation and also to evaluate the association between the presence and abundance of NZMS and water quality parameters. In addition, a genetic characterization of the Madeiran NZMS populations may clarify possible invasion pathways, as well as the origin of the population(s) now present in the island. In addition, public awareness about the topic of biological invasions needs to be raised to prevent the risk of NZMS spreading or new invasions.

Conclusions

A recent and fast colonization of NZMS has been observed in Madeira Island streams. Some potential effects on native ecosystems were identified, namely possible shifts in food webs promoted by the presence of NZMS and possible depletion of native shredders and grazers. Our results also show that catchments located in Laurisilva forest, representing the top conservation sites of Madeira Island, are at a greater risk since they have high NZMS abundances. Attention should be directed at studying the possible effects of NZMS on native grazer and detritivorous species, but also other taxonomic groups, especially in algae and fish communities. Also, and since the spread and impacts of NZMS may be facilitated by different factors related to human activities, more in-depth studies are needed to clarify the role of each type of disturbance on these benthic communities and evaluate the impacts on ecosystem services. In addition, climate change is happening at an unexpected pace; therefore, studying the relationship between invasive success and climate variables, especially within the island context, should also be pursued. As far as is known, NZMS is not present in the rest of the islands in the Macaronesia group. Since the eradication of this species is challenging, the further spread of NZMS must be minimized, and prevention of future invasions is a top priority. For that, quarantine regulations could be applied to sterilize equipment used in freshwater-related

activities. Such measures can be far more cost-effective than attempting to address the problems once the snails have invaded new streams. A crucial aspect involves raising public awareness to the intrinsic value of island freshwaters. Success in the long-term conservation of Madeira's unique biodiversity including freshwater macroinvertebrates can only be achieved through public cooperation and understanding of the potential ecological problems caused by invasive species.

Author contribution

MD: Sample processing, data analysis and interpretation, writing - original draft and writing - review & editing. **JP:** research conceptualization, data interpretation, writing - review & editing. **LM:** research conceptualization, funding provision, sample design and methodology, data interpretation, writing - review & editing.

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Supplementary material 1

Supplementary information

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Data type: docx

Explanation note: **table S1.** Physico-chemical conditions of the different sampled streams. **table S2.** Community descriptors per sampling site. **table S3.** Total abundance of each macro-invertebrate taxa per sampling site. **fig. S1.** Pearson Correlation between NZMS abundance and abiotic parameters: Conductivity (a), Temperature (b), pH (c) and Dissolved oxygen (d). NZMS abundances went through a logarithmic transformation. 95% confidence bands of the best-fit line are represented with dashed lines.

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