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A horizon scan exercise for aquatic invasive alien species in Iberian inland waters

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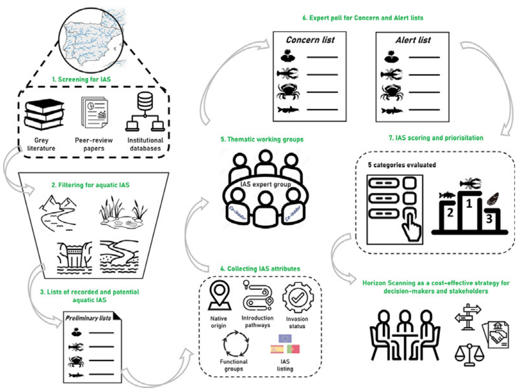
HIGHLIGHTS

- Horizon scan (HS) of aquatic IAS was performed in a European biodiversity hotspot.
- Concern and Alert list included 126 recorded and 89 potential IAS, respectively.
- IAS were scored for invasiveness, impacts, management difficulty and acceptability.
- 24 recorded and 10 potential IAS received the highest scores in expert assessment.
- Many high-scoring IAS are left out of national and European legally binding lists.

GRAPHICAL ABSTRACT



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ABSTRACT

As the number of introduced species keeps increasing unabatedly, identifying and prioritising current and potential Invasive Alien Species (IAS) has become essential to manage them. Horizon Scanning (HS), defined as an exploration of potential threats, is considered a fundamental component of IAS management. By combining scientific knowledge on taxa with expert opinion, we identified the most relevant aquatic IAS in the Iberian Peninsula, i.e., those with the greatest geographic extent (or probability of introduction), severe ecological, economic and human health impacts, greatest difficulty and acceptability of management. We highlighted the 126 most relevant IAS already present in Iberian inland waters (i.e., Concern list) and 89 with a high probability of being introduced in the near future (i.e., Alert list), of which 24 and 10 IAS, respectively, were considered as a management priority after receiving the highest scores in the expert assessment (i.e., top-ranked IAS). In both lists, aquatic IAS belonging to the four thematic groups (plants, freshwater invertebrates, estuarine invertebrates, and vertebrates) were identified as having been introduced through various pathways from different regions of the world and classified according to their main functional feeding groups. Also, the latest update of the list of IAS of Union concern pursuant to Regulation (EU) No 1143/2014 includes only 12 top-ranked IAS identified for the Iberian Peninsula, while the national lists incorporate the vast majority of them. This fact underlines the great importance of taxa prioritisation exercises at biogeographical scales as a step prior to risk analyses and their inclusion in national lists. This HS provides a robust assessment and a cost-effective strategy for decision-makers and stakeholders to prioritise the use of limited resources for IAS prevention and management. Although applied at a transnational level in a European biodiversity hotspot, this approach is designed for potential application at any geographical or administrative scale, including the continental one.

1. Introduction

Biological invasions are one of the major drivers of global change threatening biodiversity, ecosystem services, and human health (IPBES, 2019; Pyšek et al., 2020), with high monetary costs associated with their impacts and management (Diagne et al., 2021). Increasing rates of species introductions (Seebens et al., 2017), climate change (Gallardo et al., 2018) and other anthropogenic influences, such as globalisation and human-altered habitats (Didham et al., 2007; Hulme, 2021), favour the establishment and spread of alien species. Invasive alien species (IAS) comprise those taxa transported and introduced (accidentally or deliberately) by a human agency into an area outside their native range, being able to establish, becoming abundant and spreading (Blackburn et al., 2011). Recent studies have estimated at least 20,000 established alien species in the world (Pyšek et al., 2020), with about 70 % being present in Europe (EASIN Catalogue v9.9, https://easin.jrc.ec.europa.eu/, Katsanevakis et al., 2012). The number of established alien species in this continent is estimated to rise by around 64 % by 2050 (Seebens et al., 2021). Urgent action on prevention strategies to avoid the entry of alien species is therefore of paramount importance.

Due to their connection to humans and their activities, inland aquatic environments (e.g., estuarine and fresh waters, hereafter referred to as inland waters) are particularly vulnerable to IAS introduction (Strayer, 2010; Flood et al., 2020; Tickner et al., 2020; Guareschi and Wood, 2022), which often causes severe ecological and economic impacts in recipient ecosystems worldwide (Dudgeon et al., 2006; Gherardi, 2007; Gallardo et al., 2016a; Guareschi et al., 2021). Economic costs of aquatic invasions are increasing exponentially, with both damage and management costs estimated to be at least US$23 billion per year globally (Cuthbert et al., 2021). In the Iberian Peninsula, in Spain, for example, ca. €50 million have been spent on control actions for water hyacinth *Eicchornia crassipes* (= *Pontederia crassipes*) in the Guadiana basin between 2004 and 2020 (www.miteco.gob.es). Similarly to the increasing trend in alien species introductions across all environments, the number of aquatic IAS is also increasing rapidly as well as their rate of spread (Olden et al., 2022), especially in European inland waters (Nunes et al., 2015). Despite covering only 0.01 % of the total water surface area of the Earth, freshwater ecosystems harbour almost 9.5 % of the global biodiversity (Balian et al., 2008; Strayer and Dudgeon, 2010), thus managing IAS in these species-rich environments is a global priority for freshwater biodiversity conservation (Reid et al., 2019; Albert et al., 2021; van Rees et al., 2021).

Recognising the need for a coordinated set of actions devoted to preventing the introduction of IAS, controlling their established populations and mitigating their impacts, the European Parliament and the Council adopted the Regulation (EU) No 1143/2014 on the prevention and management of the introduction and spread of invasive alien species (hereinafter the EU Regulation) since January 2015 (EC, 2014). The EU Regulation sets out rules to effectively address these concerning environmental issues by seeking to prevent the entry of new IAS, creating an early warning and rapid response system, and prioritising management of highly spreading and impactful IAS (Genovesi et al., 2015; Reaser et al., 2020). According to Haubrock et al. (2021), the total costs of IAS in Member States amounted to more than €45.63 billion between 1960 and 2020, mostly due to damage losses and management affecting multiple sectors (e.g., agriculture, administration, forestry, and fisheries). Prioritising and focusing efforts on IAS that may be more problematic and more likely to be introduced in the near future is therefore of utmost importance to anticipate associated threats.

One of the main aims of the EU Regulation is the list of IAS of Union concern (hereafter, the Union list), which includes taxa highly detrimental to native biodiversity and for which concerted action is required across the European Union (Genovesi et al., 2015). This list aims not only at minimising damage from recorded IAS, but also at identifying potential invaders (Roy et al., 2018). Once established, IAS eradication becomes an arduous and often impossible task that involves high-cost management efforts (Cuthbert et al., 2022), notably in freshwater ecosystems (but see Simberloff, 2021). The development of prioritised lists of introduced or potential IAS at both national and transnational scales is a useful tool to implement robust prevention measures, design cost-effective early warning and rapid response protocols and improve current legislation (Bertolino et al., 2020; Wallace et al., 2020).

To systematically address potential threats and opportunities of IAS, which are still poorly understood, horizon scanning (HS) has proven to be a valid tool (Sutherland and Woodroof, 2009; Sutherland et al., 2011). In biological invasion science, such tools have recently emerged as a useful approach to prioritise the most threatening and emerging IAS and to support decision-making and policy. Horizon scan exercises have been conducted at national (e.g., Peyton et al., 2019; Lucy et al., 2020), transnational (e.g., Gallardo et al., 2016b), continental (e.g., Carboneras et al., 2018; Roy et al., 2019) and global scales (Vilizzi et al., 2021), as well as for specific taxonomic groups (e.g., Bayón and Vilà, 2019; Kendig et al., 2022) or particular ecosystems (e.g., Tsiamis et al., 2020). To date, most exercises typically assess the spread of IAS in a given territory, as well as the ecological, economic and human health impacts; however, the difficulty of management and societal acceptance of management are two aspects that are seldom considered. In addition, conducting HS at a transnational scale is particularly relevant when it comes to biodiversity conservation across a common biogeographic region. The Iberian Peninsula mostly comprises Spain and Portugal, which share the largest river basins and belong mainly to a single biogeographical region with similar environmental and socioeconomic conditions. This biogeographical area is a unique Mediterranean enclave with high aquatic diversity and a remarkable number of endemic species (Hewitt, 2011; Hermoso et al., 2016) currently at risk from multiple threats, including aquatic IAS (Aguiar and Ferreira, 2013; Anastácio et al., 2019; Muñoz-Mas and García-Berthou, 2020). These features coupled with marked environmental gradients and the exceptionally high richness of aquatic IAS make the Iberian Peninsula an ideal, coherent and necessary candidate for HS exercises. This will help ensuring an effective implementation of coordinated management strategies in both Spain and Portugal, given independent actions could lead to fruitless and unsuccessful results.

Here we present a HS exercise aimed at drawing up two transnational prioritised lists of aquatic alien species, including both recorded (i.e., Concern list) and potential IAS (i.e., Alert list), which pose or may pose a threat to inland waters ecosystems in the Iberian Peninsula. This HS intends to constitute an updated reference tool for informing decision-making, as well as for facilitating communication, knowledge transfer and discussion among key stakeholders, and supporting the implementation of the EU Regulation. By including four major inland water thematic groups (plants, freshwater and estuarine invertebrates, and vertebrates), this HS represents a comprehensive assessment of the main introduction pathways and relevant species-specific attributes, and provides a ranked list of aquatic IAS that should be of high priority for management in the Iberian Peninsula. The HS approach can be potentially applied at other geographical or administrative scales, including the continental scale.

2. Methods

2.1. Study area

This study covers the continental areas of Spain and Portugal, comprising nearly all the surface area of the Iberian Peninsula or Iberia (hereafter, for simplicity, we refer to the Iberian Peninsula in general). Thus, estuarine and fresh waters of the Balearic Islands and the Macaronesian archipelagos belonging to Spain and Portugal (Canary, Madeira and Azores islands) were excluded. Following the EU Water Framework Directive, we considered inland waters to be all standing or flowing waters on the land surface, and all groundwater on the landward side of the baseline from which the extent of territorial waters is measured, also including artificial and heavily modified water bodies (e.g., reservoirs).

2.2. Thematic groups and data compilation

From a full set of species previously compiled for the HS (see section below for details on the procedure), the inland aquatic alien species were divided for assessment into four biotic groups according to their taxonomy and selected environment: plants, freshwater invertebrates, estuarine invertebrates, and vertebrates. Vertebrates and invertebrates included both aquatic and semi-aquatic organisms, whereas plants included submerged, floating and emergent aquatic plants, which are mainly hydrophytes and helophytes. Only those marine taxa that commonly colonise estuarine or brackish waters were included. All regionally translocated species that are considered native in any part of the Iberian Peninsula (e.g., Iberian native species introduced in river basins outside of their native area) were not assessed.

For each alien species, experts collected information on (1) taxonomy (phylum, class, order, and family); (2) thematic group membership (plants, freshwater invertebrates, estuarine invertebrates, and vertebrates); (3) invasion status (potential, uncertain, established, and cryptogenic taxa); (4) native range (Europe, Africa, temperate Asia, tropical Asia, Australasia, Pacific, North America, and South America); (5) pathways of introduction (release, escape, contaminant, stowaway, corridor, unaided and unknown) and their subcategories (sensu CBD, 2014); (6) broad functional feeding groups were used to accommodate the different type of organisms evaluated (primary producers, filter-feeder, omnivore, detritivore, predator, and herbivore); and (7) whether the alien species is listed in the Union list, or in any list of IAS of national concern. Note that broad functional feeding groups were used as opposed to the detailed grouping normally used for specific taxonomic groups (e.g., freshwater macroinvertebrates) to accommodate the wide variety of organisms evaluated here (as in Gallardo et al., 2016b). Metadata on each species attribute and additional specific definitions are detailed in Supplementary Material (see Tables S1 and S2).

2.3. Structured and systematic approach to horizon scanning

We followed a structured 5-step structured approach that combined knowledge of biological invasion with identification and expert judgement in a continuous consensus (Fig. 1; Gallardo et al., 2016b). Participants were experts in the field of biological invasions, both researchers and managers, many specialised in Mediterranean environments in the Iberian Peninsula, with expertise in a range of taxa and biomes. Three workshops and six online meetings were held from January 2019 to October 2020 in order to develop criteria for screening and species inclusion, selecting the most impactful IAS, risk scoring and agreement about the final lists, under the coordination of the LIFE INVASAQUA Project (LIFE17 GIE/ES/000515). As a baseline for discussion, we used comparable assessments at national and international scales, and lists from previous horizon scan exercises (e.g., Almeida et al., 2013; Roy et al., 2014; Gallardo et al., 2016b; Carboneras et al., 2018; Roy et al., 2018; Nentwig et al., 2018; Peyton et al., 2019) as well as Iberian inventories of aquatic IAS (Oliva-Paterna et al., 2021a, 2021b).

Step 1: Systematic review, working groups and preliminary lists compiled

Information on alien species present and potential taxa to be introduced in the Iberian Peninsula is often scattered in various sources, such as scientific and grey literature, online and offline databases, competent regional

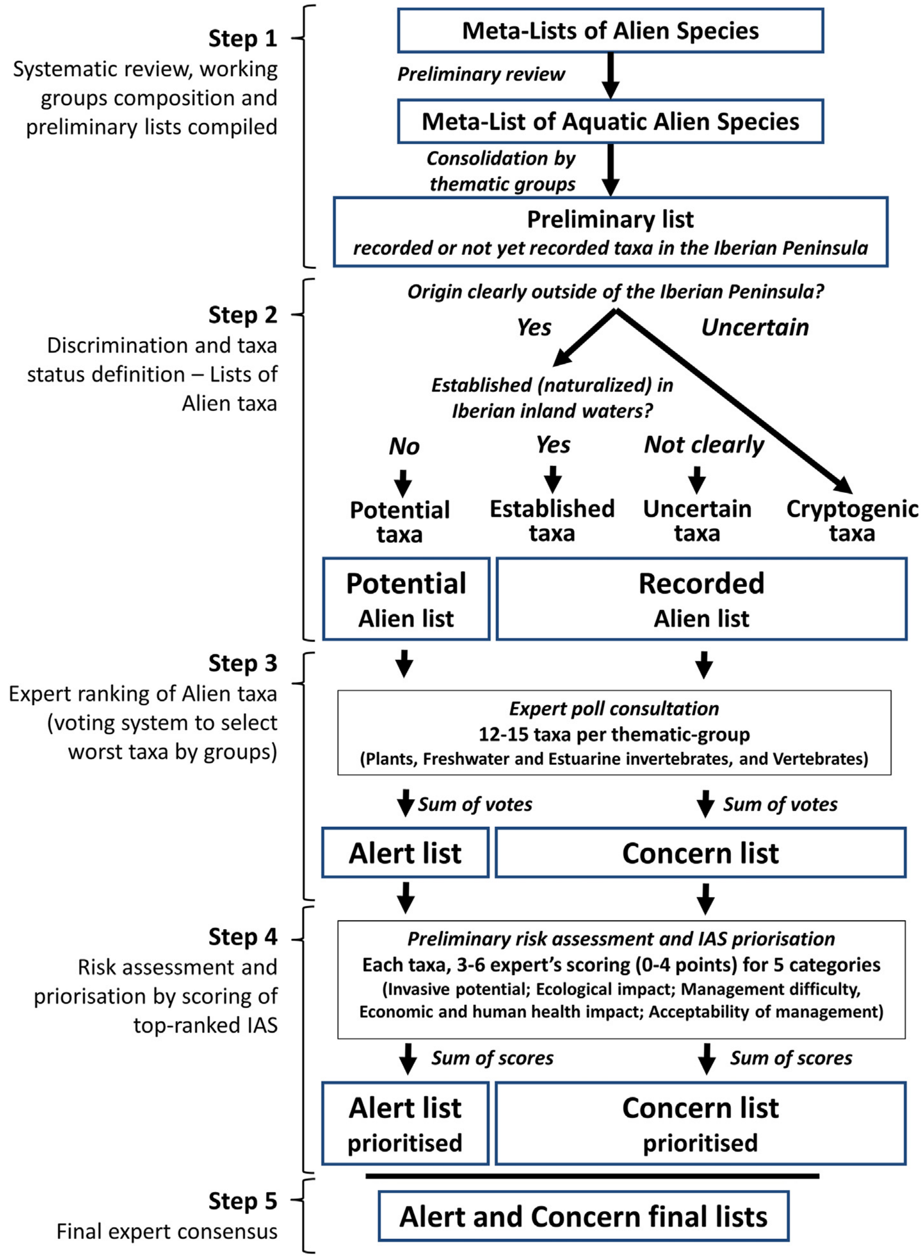

Fig. 1. Five-step structured approach used in the horizon scan exercise for identifying the most relevant potential and recorded aquatic invasive alien species (IAS) in Iberian inland waters. Modified from Gallardo et al. (2016b).

and national authorities, among others (see, for example, limitations in finding the costs incurred by IAS in Angulo et al., 2021). Thus, previously published scientific literature (e.g., García-Berthou et al., 2007; Cobo et al., 2010; Aguiar and Ferreira, 2013; Chainho et al., 2015; Anastácio et al., 2019; Muñoz-Mas and García-Berthou, 2020), available technical reports, IAS databases and other internet sources were systematically screened to obtain a meta-list of alien species. Several regional and national competent authorities and scientists supported the compilation by providing their private inventories (Oliva-Paterna et al., 2021a, 2021b).

A total of 60 experts from Spain and Portugal participated in the first steps to generate preliminary lists of recorded and potential alien species (Oliva-Paterna et al., 2021a, 2021b). They were assigned to working groups based on their expertise, covering all taxa in each of the thematic groups (see description of thematic groups above and in Tables S1 and S2). Each thematic group had at least two co-leaders (i.e., senior researchers with relevant expertise in invasion biology) to coordinate and to solve doubts in the taxa selection process. The task of compiling the preliminary lists was divided into the four thematic groups and their respective taxonomic classification was included. Experts were responsible for reviewing the preliminary list associated with their corresponding thematic group.

Step 2: Discrimination and taxa status definition – Lists of alien taxa

Once the preliminary list of IAS was compiled, the experts collected additional information to determine their native range and assess the current status of each taxon in the Iberian Peninsula. The alien species collected were classified into two classes according to whether their native range was known or unknown (i.e., cryptogenic species, those whose native range is unclear). In addition, those species with known native range were divided into three classes according to invasion status: established; uncertain if introduced but not established in the wild; or potential, if they could potentially be introduced in the near future. Through online meetings, the experts reached a consensus based on scientific literature to list the recorded (including established, uncertain and cryptogenic) and potential (not yet present) alien taxa (see Fig. 1). These two lists totalled, respectively, 275 recorded and 260 potential alien taxa for the four thematic groups.

Step 3. Expert ranking of alien taxa – Selection of most relevant taxa

As a first prioritisation step, following Burgman et al. (2014) and Gallardo et al. (2016b), we conducted an expert poll consultation with a quick and cost-effective voting system that efficiently synthesises expert perception to prioritise alien taxa. The respective experts within the thematic group identified about 20 % of most relevant alien taxa (12–15 taxa for each group-list). The most relevant alien taxa were considered to be those with likely the greatest ecological and socio-economic impact in the Iberian Peninsula under a worst-case invasion scenario. Specifically, the worst-case scenario for recorded taxa considers the full area they currently occupy and how much they could potentially expand if all preventive management measures failed; for potential taxa, the worst-case scenario is the largest area that could most likely be reached in the Iberian Peninsula if they were to arrive in the near future. Each thematic group was assessed by 12–14 experts and the score given to each alien species was the number of votes received. Note that this does not mean that taxa with few (or no) votes are free of risk, but that they have a lower perceived priority. Finally, after expert consensus, the taxa voted by at least 25 % of the experts in each thematic group formed the most relevant alien species lists (see Fig. 1). Considering the four thematic groups, a total of 126 and 89 taxa were selected as the most relevant recorded and potential alien taxa, respectively. According to the experts' consensus, all taxa included in most relevant alien taxa lists can be considered invasive alien species.

Step 4. Preliminary risk assessment and IAS prioritisation

We subsequently scored the most relevant IAS selected in step 3 following the procedure of Molnar et al. (2008) and Gallardo et al. (2016b), in which each recorded or potential alien species was assessed according to five categories that summarise important characteristics of the invasion process, ecological and socio-economic impacts as well as management possibilities (see Fig. 1; Supplementary Material – Appendix I). Since the likelihood and magnitude of the effects of biological invasion are context-dependent, the experts were again asked to assume a worst-case scenario for scoring. Each category was given a score between 0 and 4, so that the total score of an IAS was equal to the sum of the five categories (all categories were considered equally important), with a maximum of 20 points. In addition, experts provided the level of confidence for scores according to the available scientific literature. Thus, the maximum score was assigned to those IAS that are widespread (or highly likely to be introduced, in the case of potential IAS), with high ecological, economic and health impacts, and which management is very complicated and poorly accepted by society. Each IAS was assessed by 3–6 experts, and taxa with a mean score value equal to or higher than 15 comprised the top list with very high priority and risk of impact for Iberian inland waters.

Step 5. Consensus-building across expert groups

Through a final online meeting, the experts reviewed the final Concern and Alert lists and agreed on the final score for each IAS included.

2.4. Statistical analyses

To analyse the uncertainty among the experts' scores, we conducted an inter-rater reliability analysis (i.e., the degree of agreement between independent observers rating or evaluating the same phenomenon; see Gallardo et al., 2016b) applying the Krippendroff's α, which can be used regardless of the number of observers, levels of measurement, sample sizes and the presence or absence of missing data, and allows to compare ordinal values (Hayes and Krippendorff, 2007; Cano-Barbacil et al., 2020). The index takes values between 0 and 1, where 0 indicates no reliability and 1 indicates perfect reliability (Krippendorff, 2004, 2011). Krippendorff's α and its 95 % confidence intervals were obtained using the "*krippendorffs.alpha*" function of the *krippendorffsalpha* package in R v.4.2.1 (Hughes, 2021; R Core Team, 2022).

Significant differences in risk scores between the four thematic groups for each of the five categories were assessed with non-parametric Kruskal-Wallis rank sum tests, followed by pairwise Wilcoxon rank sum tests. *P*-values were corrected for multiple inferences using the Benjamini-Hochberg method. Statistical tests and graphical plots were performed with the *stats* and *ggplot2* packages in R v.4.2.1, respectively (R Core Team, 2022).

2.5. Comparison to other lists

For a more decision-oriented purpose, a final comparison exercise was carried out among IAS included in both lists (i.e., our Concern and Alert lists), the Union List (Commission Implementing Regulation No. 2016/1141, latest update 2 August 2022; EC, 2016), the Spanish IAS Catalogue (Royal Decree 630/2013, latest update 1 December 2020; BOE, 2013), the Portuguese National List of IAS (Decree-Law 92/2019; DR, 2019) and the Spanish list of allochthonous species regulating the administrative procedure for the prior authorisation of the import into the national territory of allochthonous species in order to preserve the Spanish native biodiversity (Royal Decree 570/2020; BOE, 2020). Briefly, while the Union List includes IAS of EU concern (88 IAS), the Spanish IAS catalogue and the Portuguese National List of IAS (with >200 and 340 IAS, respectively) prohibit the use, transport, and trade of those IAS of EU or national concern, the Spanish list of allochthonous taxa explicitly excludes the first two above-mentioned lists and contains >3000 alien taxa likely to be introduced, cause impacts and for which entry into the country requires prior authorisation.

3. Results

3.1. Concern list

3.1.1. Thematic groups, invasion status and taxonomy

From the first preliminary list of 306 alien taxa recorded in the Iberian inland waters, only 126 IAS were selected for the final Concern list of recorded IAS: 30.9 % vertebrates, 29.4 % estuarine invertebrates, 21.4 % freshwater invertebrates, and 18.3 % plants (Fig. 2; see Supplementary Material – Table S1 for the full database). Most of the listed species (81.7 %, 103 taxa) are clearly established or naturalised in Iberian inland waters. The majority of vertebrates corresponds to fishes (22 taxa), followed by 6 reptiles, 4 mammals, 4 birds and 3 amphibians. Freshwater and estuarine invertebrate species were dominated by molluscs and arthropods, while most of the 23 aquatic plants were angiosperms.

3.1.2. Scoring of recorded IAS

After expert-scoring (step 4), 24 species were considered as '*very high risk*' IAS for Iberian inland waters (i.e., top-ranked IAS) by reaching the highest scores (equal to or higher than 15; Table 1 and Fig. 2). The remaining IAS were categorised as high (92 taxa) or medium risk (10 taxa), with no IAS classified as low risk (Fig. 2). Within the top-ranked IAS included in the Concern list, 11 were vertebrates, 7 invertebrates (3 estuarine and 4 freshwater) and 6 plants (Table 1). Detailed information with the total number of evaluated taxa, number of expert-assessments per taxa, and ranking according to the thematic group is provided in Supplementary Material – Table S1.

The results of the inter-rater analysis showed moderately adequate reliability values for the IAS included in the Concern list, being significantly more reliable (i.e., experts agreed more) for vertebrates ($\alpha = 0.61$, 95 % CI [0.45, 0.73]), followed by freshwater invertebrates ($\alpha = 0.45$, [0.27, 0.62]), plants ($\alpha = 0.33$, [0.08, 0.55]), and estuarine invertebrates ($\alpha = 0.25$, [0.00, 0.46]). Overall, there was no clear evidence of differences between the four thematic groups when comparing the total risk scores ($\chi^2 = 6.92$, df = 3, $P = 0.0744$), except between estuarine invertebrates and vertebrates ($P = 0.046$). For further information about both analyses, see Supplementary Material – Appendix II.

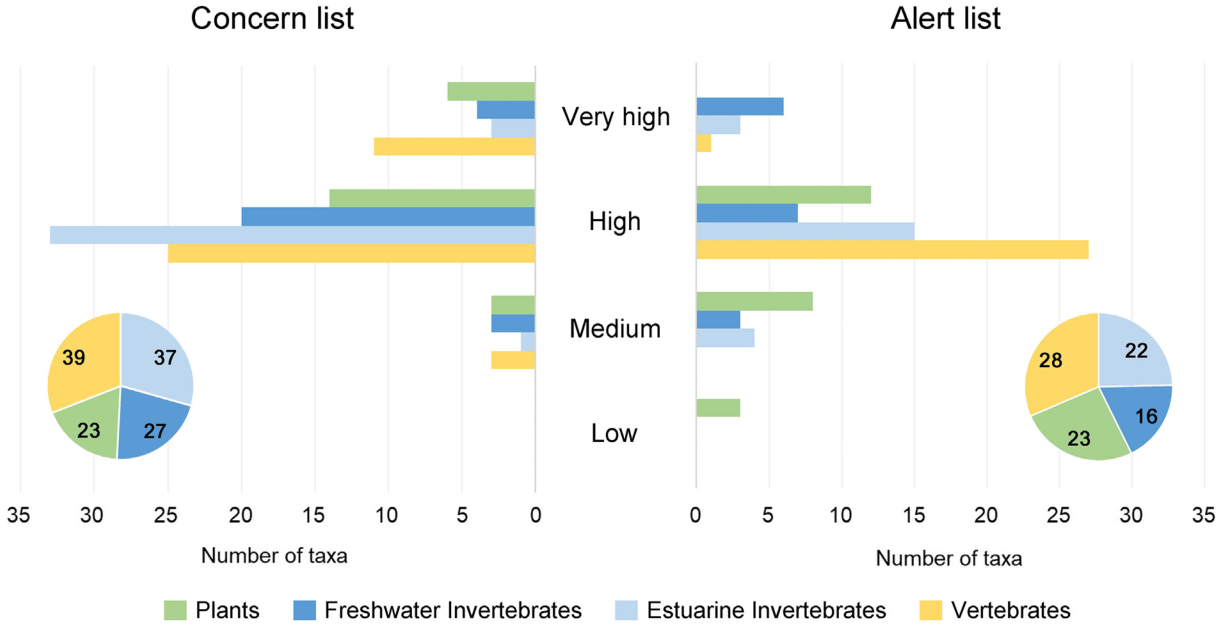

Fig. 2. Number of aquatic invasive alien species in Iberian inland waters included in the Concern (left) and Alert (right) lists ranked as *very high*, *high*, *medium*, and *low* risk through the horizon scan exercise. Embedded pie charts show the total number of taxa included in both lists according to the thematic groups.

3.1.3. Native range and introduction pathways

Most of the 126 IAS taxa recorded in the Iberian Peninsula were native to North America (46.0 %, 58 taxa) and temperate Asia (31.8 %, 40 taxa), followed by those from the Pacific region (21.4 %, 27 taxa), South America (20.6 %, 26 taxa), tropical Asia (18.3 %, 23 taxa), Europe (15.1 %, 19 taxa), Australasia (12.7 %, 16 taxa), and Africa (7.9 %, 10 taxa) (Fig. 3a). While most of the vertebrates present in the Iberian Peninsula are native to North America and temperate Asia, the Pacific region is the origin of up to 24 species of estuarine invertebrates, and almost 40 % of the invasive aquatic plants recorded are from South America. In contrast, invasive freshwater invertebrates came from all over the world with no predominant region of origin. It should be noted that there was an important group of IAS partly native to Europe (e.g., Ponto-Caspian species) considered of *very high* risk in the Iberian Peninsula (e.g., European catfish *Silurus glanis*, or zebra mussel *Dreissena polymorpha*) (see Table 1, and discussion below).

According to the expert assessment, IAS included in the Concern list reached the Iberian Peninsula through multiple introduction pathways, with 50 % of them arriving via more than one pathway. Escape from facilities was the main introduction pathway for IAS established in the Iberian Peninsula (47.6 %, 60 IAS), followed by release into the wild (36.5 %, 46 IAS), stowaway (32.5 %, 41 IAS) and contaminant (27.8 %, 35 IAS) (Supplementary Material – Table S1). Main introduction pathways varied depending on the thematic group. For instance, vertebrates were mainly introduced via releases into the wild and escapes from facilities; estuarine

Table 1

Top-ranked 24 invasive alien species included in the Concern list and evaluated by experts as having a *very high* risk for the Iberian inland waters (mean scoring value ≥15). The full Concern list is available in Supplementary Material – Table S1. The corresponding thematic group, score value (mean ± standard deviation), scientific name, native range, the main introduction pathway, and functional group are shown.

Thematic-group	Score (mean ± SD)	Scientific name	Native range	Pathway of introduction	Functional group
Plants	16.7 ± 0.7	*Eichhornia crassipes* (Mart.) Solms	SAm	Esc	Prim Prod
	16.2 ± 0.2	*Azolla filiculoides* Lam.	NAm, SAm	Cont	Prim Prod
	15.8 ± 0.5	*Ludwigia grandiflora* (Michx.) Greuter & Burdet	NAm, SAm	Rel, Esc	Prim Prod
	15.7 ± 1.2	*Salvinia natans* (L.) All.	NAm, SAm	Rel, Esc	Prim Prod
	15.4 ± 1.1	*Salvinia molesta* D.S.Mitch.	SAm	Rel, Esc	Prim Prod
	15.3 ± 1.1	*Spartina densiflora* Brongn.	NAm	Stow	Prim Prod
Freshwater Invertebrates	18.7 ± 0.6	*Procambarus clarkii* (Girard, 1852)	NAm	Rel, Esc	Omni
	17.3 ± 0.3	*Dreissena polymorpha* (Pallas, 1771)	As, Eur	Cont, Stow	Filter
	17.3 ± 0.9	*Pacifastacus leniusculus* (Dana, 1852)	NAm	Rel, Esc	Omni
	17.0 ± 0.4	*Corbicula fluminea* (O.F.Müller, 1774)	As, At	Rel, Cont, Stow, Unaid	Filter
Estuarine Invertebrates	16.0 ± 0.7	*Ficopomatus enigmaticus* (Fauvel, 1923)	Pac, Aus	Cont, Stow	Filter
	16.0 ± 0.9	*Magallana gigas* (Thunberg, 1793)	Pac, As	Esc	Filter
	15.2 ± 0.7	*Callinectes sapidus* Rathbun, 1896	NAm, SAm	Stow, Unaid	Omni
Vertebrates	18.2 ± 0.4	*Cyprinus carpio* Linnaeus, 1758	Eur, As	Rel, Esc	Omni
	17.2 ± 0.4	*Micropterus salmoides* (Lacepède, 1802)	NAm	Rel	Pred
	16.3 ± 0.6	*Sander lucioperca* (Linnaeus, 1758)	Eur, As	Rel	Pred
	16.2 ± 0.4	*Silurus glanis* Linnaeus, 1758	Eur, As	Rel	Pred
	16.2 ± 0.7	*Gambusia holbrooki* Girard, 1859	NAm	Rel	Omni
	16.0 ± 0.3	*Esox lucius* Linnaeus, 1758	Eur, As, NAm	Rel	Pred
	15.8 ± 0.4	*Pseudorasbora parva* (Temminck & Schlegel, 1846)	As	Rel, Esc	Omni

Native range: Eur, Europe; As, Asia-temperate; At, Asia-tropical; Aus, Australasia; Pac, Pacific; NAm, North America; SAm, South America. **Pathway of introduction**: Rel, Release; Esc, Escape; Cont, Contaminant; Stow, Stowaway; Unaid, Unaided. **Functional group**: Prim Prod, Primary producers; Omni, Omnivores; Pred, Predators; Herb, Herbivores; Filter, Filter feeders.

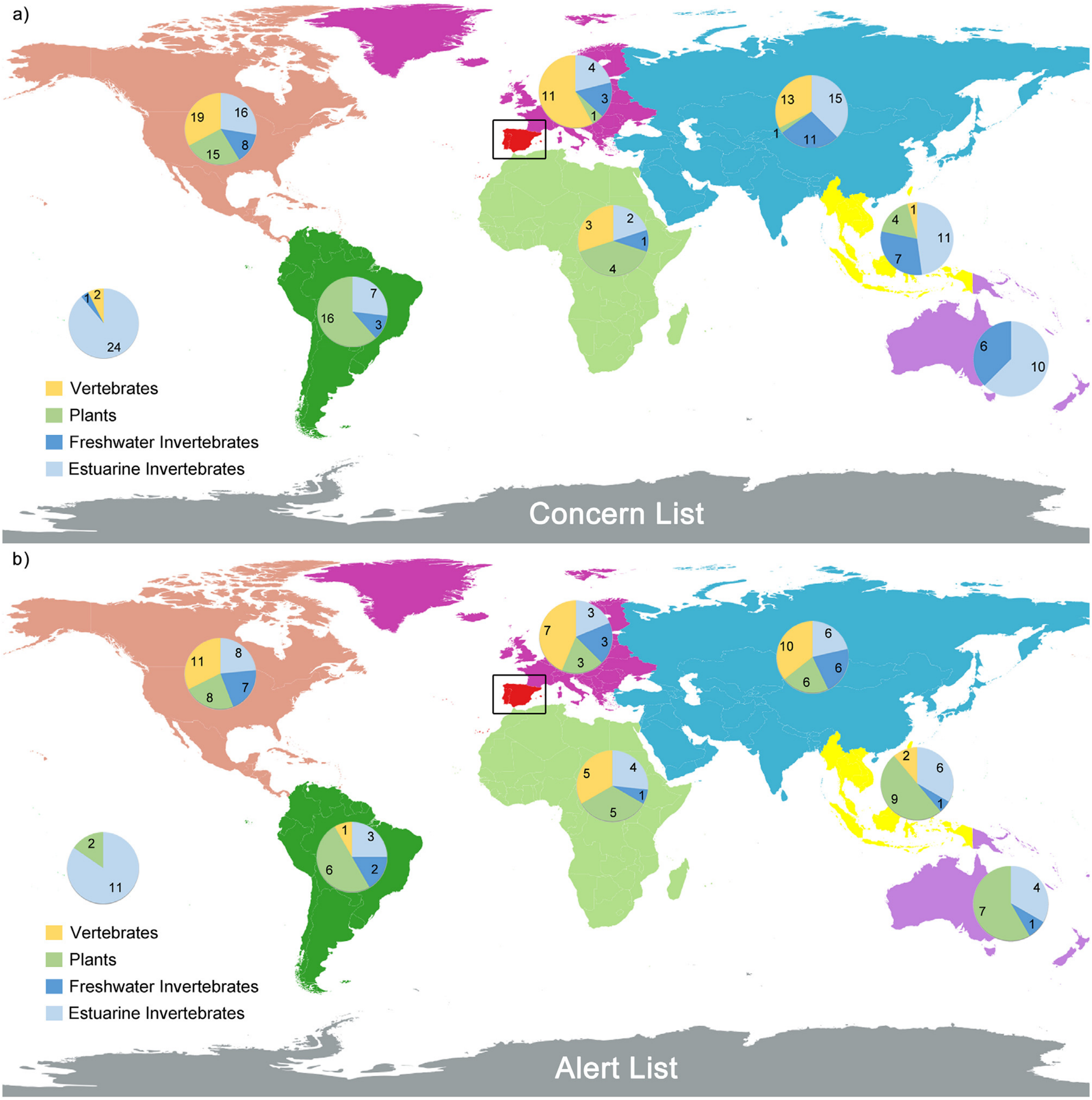

Fig. 3.

Distribution and number of aquatic invasive alien species (IAS) (a) recorded (Concern list) and (b) potentially to be introduced (Alert list) in the Iberian inland waters according to their native regions. The native regions considered are coloured differently on the map, note that the map resolution is insufficient for the Pacific Islands. The study area, the Iberian Peninsula, is framed and highlighted in red. Each pie chart indicates the number of IAS native to the region and the colours show the four thematic groups. Note that the total number of IAS exceeds the number of species included in the lists because some species can be native to more than one region (for details, see Tables S1 and S2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

invertebrates mainly as stowaways and contaminants; freshwater invertebrates did so through releases, escapes, as contaminants and as stowaways in roughly equal proportions; and finally, most plants were introduced via escapes from facilities (Fig. 4).

3.1.4. Functional groups for recorded IAS

The IAS included in the Concern list spanned a variety of functional groups, with filter feeders and omnivores being the most represented, followed by predators and primary producers (Fig. 5). As expected, primary producers were dominated exclusively by plants, while the vast majority of vertebrates were omnivores and predators. A pattern can be appreciated with most of the estuarine invertebrates being filter feeders, whereas freshwater invertebrates presented more heterogeneous feeding habits (omnivores, predators or filter feeders in similar proportions).

3.2. Alert list

3.2.1. Taxonomy and thematic groups

The first preliminary list identified 272 potential alien species with high risk of invasion – but not yet recorded – in the Iberian inland waters, of which only 32.7 % (89 taxa) were included in the final Alert list: 42.7 % invertebrates (22 estuarine and 16 freshwater), 31.5 % vertebrates, and 25.8 % plants (Fig. 2). The 38 invertebrates were mainly arthropods (18 taxa) and molluscs (14 taxa). A large proportion of vertebrates were fishes (25

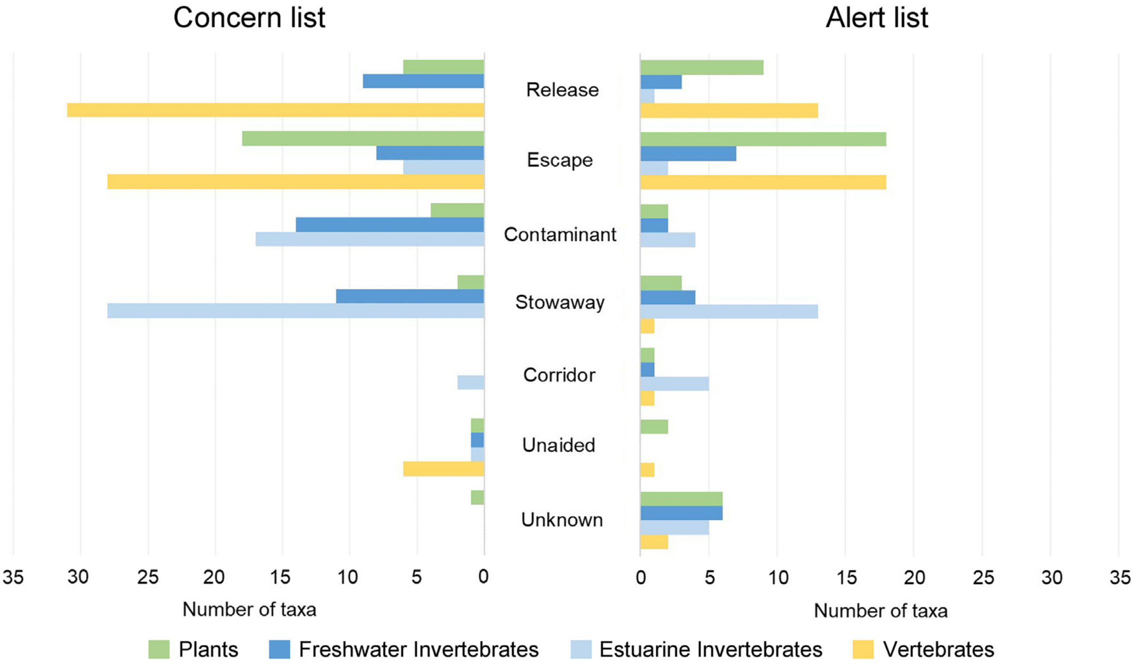

Fig. 4. Main introduction pathways for the aquatic invasive alien species (IAS) included in the Concern list (left) and Alert list (right) in the Iberian inland waters. Each axis represents the number of IAS associated with a specific introduction pathway. Note that some species may have more than one known or potential introduction pathway.

taxa), followed by 2 mammals, and 1 amphibian. Finally, 21 of the 23 aquatic plant taxa were angiosperms.

3.2.2. Scoring of potential IAS

Following expert scoring (step 4), only 10 potential IAS were classified as '*very high*' risk for Iberian inland waters (score equal to or higher than 15; Fig. 2). The vast majority of potential IAS were classified as *high* risk (61 taxa), followed by 15 taxa with *medium* risk, and only three taxa as *low* risk (Fig. 2). Notably, 6 of the top-ranked 10 IAS were freshwater invertebrates, 3 estuarine invertebrates, and only 1 vertebrate, whereas no plants were included (Table 2). Detailed information with the total number of taxa assessed, the number of expert assessments per species and the ranking according to the thematic group is provided in Supplementary Material – Table S2.

Regarding the Alert list, the α values of the inter-rater analysis for each group were slightly lower than those in the Concern list, and often non-significant. The total risk scores for IAS were significantly different in the four thematic groups ($\chi^2 = 29.3$, df = 3, $P < 0.001$), due to the fact that the scores of plants (mean ± SD, 8.9 ± 3.0) were significantly lower than those of vertebrates (13.1 ± 1.3; $P < 0.001$), freshwater invertebrates (13.1 ± 2.9; $P < 0.001$), and estuarine invertebrates (12.1 ± 2.2; $P < 0.01$). For further information about both analyses, see Supplementary Material – Appendix II.

3.2.3. Native range and introduction pathways of potential IAS

Like the Concern list, a large number of taxa included in the Alert list are native to North America (38.2 %, 34 taxa) and temperate Asia (31.5 %, 28 taxa), followed by tropical Asia (20.2 %, 18 taxa), Europe (18.0 %, 16 taxa), Africa (16.9 %, 15 taxa), the Pacific region (14.6 %, 13 taxa), South America (13.5 %, 12 taxa), and Australasia (13.5 %, 12 taxa) (Fig. 3b). In the case of the Alert list, there is a slight increase in African taxa to the

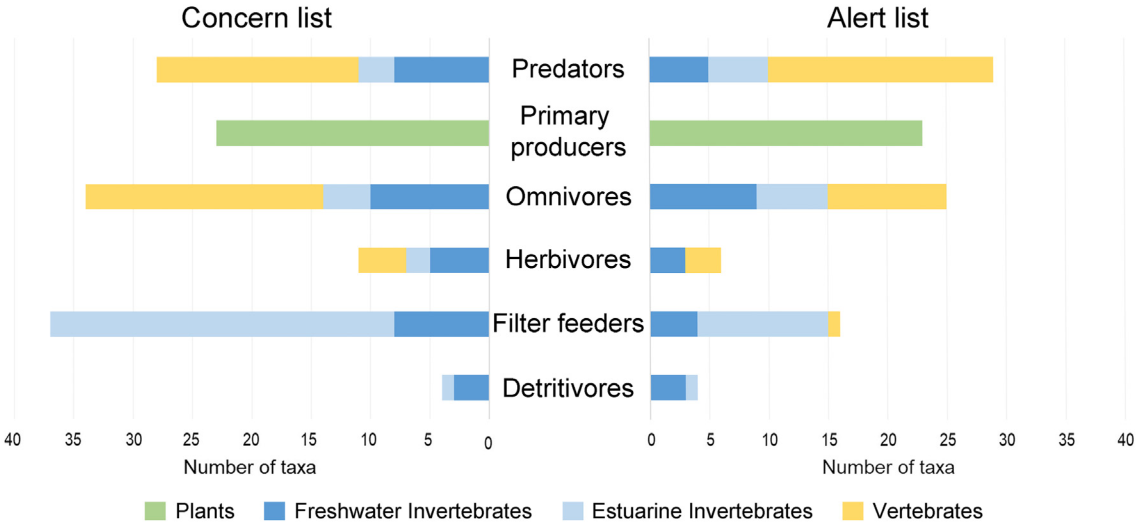

Fig. 5. Number of aquatic invasive alien species in recorded (Concern list) and potentially to be introduced (Alert list) in Iberian inland waters according to their different functional groups. Note that some species may be considered into more than one functional group.

Table 2

Top-ranked 10 invasive alien species (IAS) included in the Alert list evaluated as potentially having a *very high* risk for the Iberian inland waters (mean scoring value ≥15). No invasive alien plants were listed (i.e., mean scoring value was lower than 15). The full Alert list is available in Supplementary Material – Table S2. The thematic group, score value (mean ± standard deviation), scientific name, native range, main introduction pathway, and functional group are shown.

Thematic-group	Score (mean ± SD)	Scientific name	Native range	Pathway of introduction	Functional group
Freshwater Invertebrates	17.0 ± 0.6	*Dreissena rostriformis bugensis* Andrusov, 1897	As, Eur	Stow	Filter
	16.2 ± 1.1	*Procambarus virginalis*[a] Lyko, 2017	NAm	Rel, Esc	Omni
	15.5 ± 1.0	*Faxonius rusticus* (Girard, 1852)	NAm	Rel, Esc	Omni
	15.3 ± 0.8	*Pomacea canaliculata* (Lamarck, 1822)	SAm	Esc	Herb
	15.3 ± 0.8	*Aedes aegypti* (Linnaeus, 1762)	Afr	Cont, Stow	Pred, Filter
	15.2 ± 1.2	*Faxonius virilis* (Hagen, 1870)	NAm	Rel, Esc	Omni
Estuarine Invertebrates	15.7 ± 1.3	*Hydroides dirampha* Mörch, 1863	Aus	Stow	Filter
	15.3 ± 0.3	*Perna viridis* (Linnaeus, 1758)	As, At, Pac	Unknown	Filter
	15.0 ± 0.0	*Rhopilema nomadica* Galil, Spanier & Ferguson, 1990	Afr, As, At, Pac	Corridor	Omni
Vertebrates	15.2 ± 0.6	*Perccottus glenii* Dybowski, 1877	As	Rel, Esc	Omni

Native range: Afr, Africa; As, Asia-temperate; At, Asia-tropical; Aus, Australasia; Eur, Europe; NAm, North America; Pac, Pacific; SAm, South America. **Pathway of introduction**: Rel, Release; Esc, Escape; Cont, Contaminant; Stow, Stowaway; Corridor; Unknown. **Functional group**: Filter, Filter feeders; Omni, Omnivores; Pred, Predators; Herb, Herbivores.

[a] This crayfish species has been presumably found in Iberian inland waters during the writing process of this study.

detriment of those native to the Pacific region and South America (Fig. 3b) compared to the Concern list.

According to the experts' assessment, IAS in the Alert list could reach the Iberian Peninsula through multiple or unknown introduction pathways (Supplementary Material - Table S2), being the escape from facilities the main pathway (50.6 %, 45 IAS), followed by release into the wild (29.2 %, 26 IAS) and stowaway (23.6 %, 21 IAS). Estuarine invertebrates, vertebrates, and plants mostly followed the introduction pathways of those IAS already recorded in the Iberian Peninsula (Fig. 4). However, a remarkable change was noted for freshwater invertebrates, most of which may potentially be introduced through escapes from facilities compared to other introduction pathways. A general increase (except for vertebrates) in the lack of knowledge of the introduction pathways for many potential IAS was observed (Fig. 4).

3.2.4. Functional groups for the potential IAS

The IAS included in the Alert list encompassed a similar variety of functional groups as those of the Concern list, with less proportion of filter feeders and omnivores. As expected, primary producers were dominated exclusively by plants, while vertebrates were predators and, to a lesser extent, omnivores and herbivores. Regarding invertebrates, almost half of the estuarine invertebrates were filter feeders, while freshwater invertebrates had no predominant functional group, with omnivores being the most represented (Fig. 5).

3.3. Listed IAS representation in European and National lists

Of the 126 IAS included in the Concern list, only 28 are in the latest update of the Union list (note that the European list excludes invasive alien species native to any of the Member States), whereas 66 are in the Spanish IAS Catalogue and 63 in the Portuguese National List of IAS (Fig. 6a). While >70 % of IAS included in the Concern list are considered as '*high*' risk in Iberian inland waters, many of them are still excluded from the EU and National lists. In contrast, if we also consider the species included in the Spanish list of allochthonous species (83 species), only eight '*high*' and two *'medium'* risk IAS still remain outside any of the four legally binding lists mentioned above. Focusing on the top-ranked 24 IAS (i.e., '*very high*' risk), only one third of them are included in the Union list (Fig. 6a), nevertheless, >90 % are included in the Spanish Catalogue and >70 % in the Portuguese National List.

Regarding the Alert list (89 potential IAS), 12 are included in the latest update of the Union List, 16 in the Portuguese National List and 15 in the Spanish Catalogue (Fig. 6b), with only seven species shared in both national lists. However, >75 % of potential IAS were covered by the Spanish list of allochthonous species, thus representing an apparently higher level of biosecurity at the national scale. In general, although there were many IAS considered as '*high*' risk, the vast majority are not included in any national list and are only included in the Spanish list of allochthonous species (Fig. 6b).

4. Discussion

Our horizon scanning (HS) pointed out 126 and 89 IAS as the most relevant taxa recorded (i.e., Concern list) and potential to invade the Iberian inland waters in the near future (i.e., Alert list), respectively. Following a 5-step procedure for scoring taxa, a total of 24 recorded IAS and 10 potential IAS were considered the most notable (overall score ≥15) in terms of geographical extent (or likelihood of introduction), ecological, economic and human health impacts, difficulty and acceptability of management. While the Concern list included representatives of all four thematic groups among the top-ranked IAS, mainly vertebrates (11 taxa) and aquatic plants (6 taxa), the Alert list included mainly freshwater (6 taxa) and estuarine (3 taxa) invertebrates, and no plants. The introduction pathways varied mostly by thematic group rather than between lists, with some of them, especially in the Alert list, still unknown. In addition, we stressed that, albeit in lower numbers for the national lists of concern, many of the most notable IAS considered in the HS fall outside the legally binding listings. Therefore, our HS exercise lays down the basis for future implementation of actions and facilitates decision-making for IAS management across Iberian inland waters.

4.1. Concern list of IAS in Iberian inland waters

Based on our prioritisation exercise, 126 species were included in the Concern list as the most relevant IAS for the Iberian Peninsula, with 68.3 % present in both Spain and Portugal and many of them occupying a large geographical extent. This shows the long-lasting invasion history and high level of biological exchange among Iberian river basins (Clavero and García-Berthou, 2006; Muñoz-Mas and García-Berthou, 2020). The Iberian Peninsula is considered a hotspot for non-native freshwater fish species, where they exert multiple impacts on native biodiversity (Leunda, 2010). In fact, fishes were dominant in the present Concern list and among the taxa with the highest scores there were two fishes with a long history of invasion in the Iberian Peninsula, namely the common carp (*Cyprinus carpio*) and the black bass (*Micropterus salmoides*). This is consistent with a previous risk identification assessment that assigned high risk scores to these two species (Almeida et al., 2013). Overall, although the most representative thematic groups in terms of numbers of IAS were vertebrates and plants, freshwater invertebrates received the highest scores among the 24 top-ranked IAS. This is not surprising as many species of invasive freshwater invertebrates such as the four highest scoring freshwater invertebrates listed here (*Procambarus clarkii*, *Pacifastacus leniusculus*, *Dreissena polymorpha* and *Corbicula fluminea*) are considered important ecosystem engineers, thus impacting on key ecological processes and changing

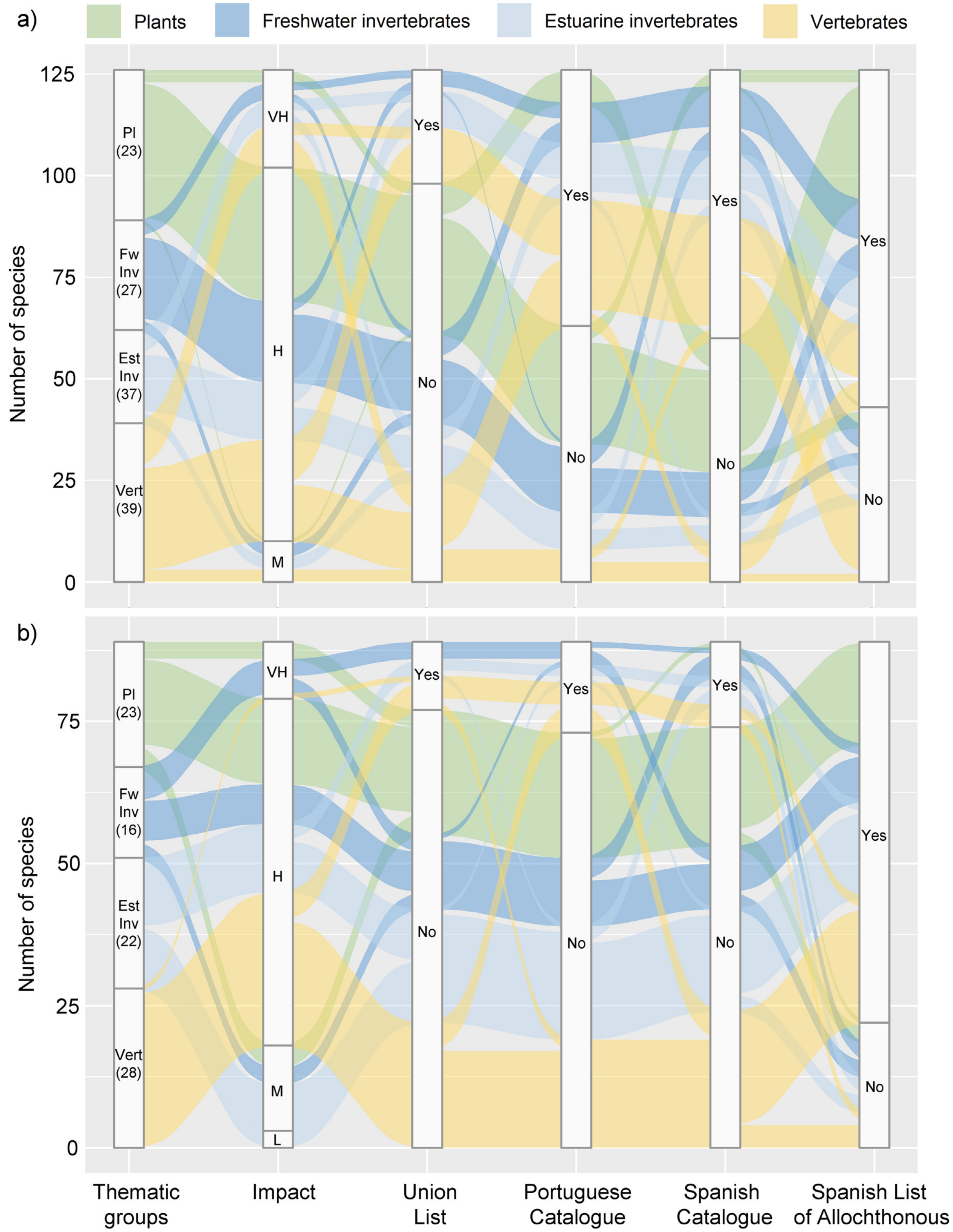

Fig. 6. Alluvial plot showing the number of (a) recorded and (b) potentially introduced invasive alien species (IAS) in Iberian inland waters, catalogued according to the thematic group, their impact, and their inclusion to European Union, Portuguese, and Spanish lists. Originating nodes and coloured flows in this diagram correspond to the thematic groups with sample size in brackets. The second node labels correspond to the impact attributed to IAS (VH, very high; H, high; M, medium; and L, low risk). The last four node labels correspond to the inclusion of IAS from the Concern (a) and Alert (b) list in each of these legally binding lists. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

entire ecosystems to suit their own needs (Emery-Butcher et al., 2020). Also, zooming in on the partial scores, the impact that the above-mentioned species have on key economic sectors is generally higher than the rest, which pushes them to the top of the ranking (see Supplementary Material – Appendix III and Table S3). In addition, they have already invaded large areas in the Iberian Peninsula (Vedia and Miranda, 2013; Oficialdegui et al., 2020b), their multifaceted impacts have been already stressed from several perspectives (Gallardo et al., 2016a; Cuthbert et al., 2021), and their management can generate social controversy because of associated socio-economic implications (Mancinelli et al., 2017; Oficialdegui et al., 2020a). In contrast, species from marine environments that can potentially affect estuaries are often under-represented in national or European lists, despite the fact that some of them have a high impact and are considered a priority (see Tsiamis et al., 2020). This under-representation is likely due to the paucity of information on the impacts of the vast majority of estuarine and marine invasions, but also to an insufficiency of taxonomic expertise for several marine smaller-bodied groups (Bailey et al., 2020). Our HS exercise however highlighted three priority species that were assessed as '*very high*' (i.e., *Ficopomatus enigmaticus*, *Magallana gigas*, and *Callinectes sapidus*). However, neither the Union List nor the National IAS lists include them (only the first one is listed in the Spanish IAS Catalogue) as a priority despite their known ecological and socio-economic impacts (López and Richter, 2017; Des et al., 2022; Clavero et al., 2022, respectively for each of the above-mentioned IAS).

Although the management of IAS in Spain and Portugal is decentralised (i.e. competences of the Autonomous Communities or Regional Government and, in some cases, of the hydrographic confederations for freshwater IAS), the scarcity of high impact IAS management strategies at national level is worrying. Our Concern list highlighted a top-ranked 24 IAS, of which species-specific management strategies have only been adopted for the water hyacinth (*E. crassipes*), zebra mussel (*D. polymorpha*) and American mink (*Neovison vison*) in Spain (www.miteco.gob.es); and for apple snails (*Pomacea* spp.) (www.dgav.pt) and invasive crustaceans such as the red swamp crayfish (*P. clarkii*), the signal crayfish (*P. leniusculus*) and the Chinese mitten crab (*Eriocheir sinensis* H.Milne Edwards, 1853) in Portugal (www.dre.pt). The management of some of the top-ranked IAS on the Iberian Peninsula is extremely difficult (an average score of 3.6 out of 4) and their control is only partially accepted by society, as some potential conflicts with certain commercial-interest species are still present (an average score of 2.3 out of 4), as for example, the exploitation of red swamp crayfish in southern Spain and Portugal (see in Souty-Grosset et al., 2016; Oficialdegui et al., 2020a). Hence, the Concern list aims to help in the prioritisation of the management of IAS that are already present in the Iberian Peninsula, which is a key input for subsequent risk assessments aimed to support strategic and legislative decision-making (Roy et al., 2018).

4.2. Alert list of IAS in Iberian inland waters

An effective biosecurity strategy involves assessing the potentially most dangerous IAS and knowing their pathways of introduction to prevent their entry and likely impacts (McGeoch et al., 2016). Overall, the score values in the Alert list were relatively lower than those attributed to IAS from the Concern list (Supplementary Material – Appendix III), which may indicate a certain lack of knowledge about the ecology and introduction pathways of species that have not yet been detected in the Iberian Peninsula. This assumption is also supported by the increased uncertainty among experts when assessing potentially introduced IAS. In addition to generating a prioritised list of potentially introduced IAS, HS exercises also aim to identify the main introduction pathways so as to prevent their entry (see Roy et al., 2014). How incoming IAS enter and how to deal with them (i.e., explicit pro-active management actions and their effectiveness) can prevent major impacts (Hulme, 2009) and optimise economic resources (Cuthbert et al., 2022). However, the introduction pathway is still unknown for a relatively high percentage of IAS included in the Alert list (21.3 %, 19 species). In the case of the 10 top-ranked IAS included in the Alert list, multiple pathways of introduction are considered (Table 2), such a range of possibilities could lead to an even greater effort for authorities to manage and prevent their entry. However, several of them are closely related to human activities such as fishkeeping, recreational fishing and shipping. In these cases, public awareness projects focusing on biosecurity and prevention of IAS introduction through surveillance programs can be particularly relevant (Thomas et al., 2017), further contributing to freshwater species conservation (Tricarico, 2022). Estuarine IAS presented different introduction pathways than freshwater taxa, though many of them showed unknown pathways, so more research is urgently needed on this thematic group (Tsiamis et al., 2020).

Many of the top-ranked IAS included in the Alert list are already established in the wild in Europe, as for example, the crayfish *Faxonius rusticus* and *F. virilis* (Kouba et al., 2014), the fish *Perccottus glenii* (Reshetnikov, 2010), or the yellow fever mosquito *Aedes aegypti* (Santos et al., 2022). Other top IAS potentially introduced in Iberian inland waters show a worldwide distribution, therefore their chances to colonise the study area are considerably high (e.g., the mussel *Perna viridis*, or the serpulid tubeworm *Hydroides dirampha*). Although our work has not focused solely on fish, the list incorporates >60 % of the fishes described by Clavero (2011) as the most likely to become new invaders in the Iberian Peninsula. Despite slight methodological differences, it is important to note that only 18 IAS presented in our Alert list are included in the preliminary list of 249 IAS (including also terrestrial and marine IAS, and covering all member states) that could threaten the EU's biodiversity and ecosystems according to Roy et al. (2019). The Alert list provided here is intended to lay the groundwork for promoting proactive management strategies devoted to preventing the potentially most harmful IAS from colonising and damaging Iberian inland waters. Hence, cooperative and transnational research and management programmes between neighbouring countries – as described here – might be established and implemented to meet the objectives proposed in the Art. 11 "Invasive alien species of regional concern and species native to the Union" and Art. 22 "Cooperation and coordination" of EU Regulation (EC, 2014) and to safeguard the European aquatic biodiversity from the impact of IAS.

4.3. Horizon scan exercise for the Iberian Peninsula

The outcome of HS exercises may not always be predictable and repeatable even if based on scientific evidence such as the likelihood of introduction pathways and known impact scores, among others. This is because they include a partly subjective component in expert opinion, which may not lead to a unique result every time (see the variability in reliability analysis, e.g., Gallardo et al., 2016b, but see Bernardo-Madrid et al., 2022). Therefore, it is of utmost importance to follow a consensus approach, screening the most detrimental IAS first and discussing the final results of the scores, which is especially relevant for IAS for which less scientific knowledge is available. Similar approaches in previous HS exercises for alien species at different scales (see above-mentioned studies) have been successful in predicting alien species introduction (Roy et al., 2019), as evidenced by the detection of seven of the top ten IAS highlighted by Roy et al. (2014). Furthermore, the level of uncertainty of each score value is key to convey the robustness of the results obtained to other audiences (see, for example, Table S3).

In addition to the subjective component of the experts, HS reflects the specific particularities of each study area, not necessarily highlighting the same species in some countries or biogeographic regions as in others (see approach used in Matthews et al., 2017). Furthermore, comparison between HS exercises in terms of species included or patterns across thematic groups is often hampered by the application of different prioritisation criteria, time frame, among others (Czechowska et al., 2022). For instance, Roy et al. (2019) used an impact scoring system based on the severity of impacts on native species and ecosystem functioning and services. Peyton et al. (2019) also included impacts on human health, Lucy et al. (2020) considered the likelihood of arrival and establishment/spread, whereas Gallardo et al. (2016b) also included the management difficulty. However, our HS expands these previous studies by additionally assessing how acceptable species-specific management is to society. Attending to the human dimension of biological invasions, a comprehensive assessment of the social acceptance of IAS management is pivotal for an effective implementation of control and prevention measures (Crowley et al., 2016), which necessarily involves close collaboration with key stakeholders and implication of the society as a whole.

Although this HS exercise only focused on Spanish and Portuguese inland waters, our results could serve as a baseline for the territories of Andorra and Gibraltar, as some headwater tributaries originating in Andorra flow into the river basins of north-eastern Spain, and Gibraltar may be an important gateway for estuarine species or IAS from other thematic groups. Due to the increase in introductions of alien species expected in the coming decades (Seebens et al., 2021), updating the HS lists periodically is of paramount importance. First, some IAS may have become established in the study area since the list was planned. This is the case of the estuarine bivalve (*Brachidontes pharaonis* (P.Fischer, 1870)), the freshwater mollusc (*Cipangopaludina chinensis* (Gray, 1833)) and the presumed recent finding of the marbled crayfish (*Procambarus virginalis*) which, after the HS exercise, have been introduced in the Iberian Peninsula (see Murcia Requena et al., 2020; Hernández et al., 2020; A. Arias, pers. comm. 2022; respectively). There are also species such as *Cynoscion regalis* (Bloch & Schneider, 1801) which, although included in the preliminary list, did not receive enough votes in the poll consultation to be included in the list of Concern; however, its populations in Portuguese and southern Spanish estuaries are increasing and its impacts could be relevant in the near future (Morais et al., 2017; Jose A. Cuesta, pers. comm. 2022). Secondly, new research may shed light on some unknown aspects (e.g., pathways of introduction or impacts) of less studied species that were not present in the past. As such, the Concern and Alert lists compiled in this study constitute an important baseline against which to monitor changes in IAS trends, as well as the effectiveness of IAS policies and management.

4.4. Evaluating legally binding IAS lists at Union and national level

The inclusion of an IAS on the Union list implies that strategic measures must be taken to address them under the EU Regulation (Genovesi et al., 2015). National lists similarly do this, usually entailing a generic ban on the possession, transport and trade of the most harmful IAS. Only 28 out of the 126 IAS recorded in Iberian inland waters are included in the Union List. Although low, these figures seem reasonable as the Union list covers a total of 27 countries belonging to different biogeographical regions. However, both national IAS lists include about half of the recorded taxa, which supports the importance of these legal instruments in addressing EU regulation at a national scale. In fact, a high number of IAS considered as '*very high*' risk are listed in both Spanish and Portuguese catalogues. Interestingly, only two top-priority IAS (*C. sapidus* and *M. gigas*) –both being estuarine invertebrates– are not included in either list to date, though they are considered in the Spanish list of allochthonous species. The legislation of commercially exploitable IAS with socio-economic benefits for certain stakeholders increases the complexity of the legal scenario, as for example, the American Mink (*N. vison*) in Denmark (see Tollington et al., 2017), the red swamp crayfish (*P. clarkii*) in Spain and Portugal (see references above) or the Atlantic blue crab (*C. sapidus*) in the list of commercial fishing species of Spain (Box et al., 2020). The potential socio-economic benefit from exploiting some IAS such as the Pacific oyster through aquaculture (Des et al., 2022) and the Atlantic blue crab through fisheries (Mancinelli et al., 2017) can generate certain social conflicts when stakeholders (e.g., fishermen) oppose the management of these harmful IAS (Grechi et al., 2014; Gago et al., 2016; Oficialdegui et al., 2020a). On the other hand, about 70 % of IAS included in the Concern list were considered as '*high risk*' to Iberian inland waters, being the vast majority excluded from the EU and national lists. The relative lack of legislative protection against IAS that pose a high risk is a reason to promote the updating of the lists and risk assessment beyond the top-priority IAS.

Our HS revealed that an evident proportion of IAS is partly native to the EU (i.e., species that are native to one member state but invasive in another), thus placing important challenges for transnational regulation and cooperation at continental scale. This exercise provides a good opportunity to underline the importance of applying Art. 11 and Art. 22 of the EU IAS Regulation, something that has been applied on few, if any, occasions. The EU Regulation largely reserves these species for national regulations, although some of them (e.g., *S. glanis*) pose highly detrimental impacts in Iberian inland waters (Carol et al., 2009; Rodriguez-Labajos et al., 2009). The identification of harmful IAS that fall outside European legislation and the assessment of their impacts on non-native range territories expedites their inclusion in national lists, reinforcing the implementation of management actions at national level.

Therefore, HS serves to alert public agencies on the arrival of potentially harmful IAS. While a very low percentage of the IAS on the alert list are currently included in national and EU lists, three-quarters of them are on the Spanish list of allochthonous species (RD 570/2020; BOE, 2020), requiring a permit and risk analysis prior to introduction, which is a major achievement in terms of biosecurity at national level.

4.5. Management implications, challenges and future research directions

Policymaking tends to act on today's problems while often ignoring incoming threats. This HS is the first step in identifying and prioritising aquatic IAS to develop proactive management in inland waters from the Iberian Peninsula. In this way, we bring aquatic IAS issues to the forefront of public knowledge and policy decisions, and help to focus future research. Despite the Iberian Peninsula long-lasting invasion history, there is often a time lag between when a species is detected, its impacts are known, and risk assessments are conducted (see Zenetos et al., 2019). Therefore, the inventories provided here are intended to highlight priority IAS for developing and implementing management strategies later on. Spain and Portugal are, however, the Member States that have made the greatest efforts to include IAS of national concern in their legally binding lists, beyond the IAS included in the Union list (Baquero et al., 2021). Even with the Spanish list of allochthonous species (RD 570/2020; BOE, 2020), we stress that there is a large percentage of 'door-knocker species' for which the pathway of introduction is still unknown, hence further research is needed to address approaching threats. Similarly, for many IAS, basic aspects of their biology and ecology in both native and invaded ranges as well as their taxonomy are poorly studied, which can often hinder proper targeting of management efforts (e.g., *Didemnum vexillum* (Kott, 2002), Fletcher and Forrest, 2011; Zhan et al., 2015). For cryptogenic species, clarifying their biogeographic status or taxonomic identity is of paramount importance, as the lack of knowledge can contribute to underestimating the number of non-native species in a given area and, consequently, their inclusion in IAS lists (Carlton, 2009).

Globalised trade is a driver of biological invasions, breaking down the natural biogeographical boundaries of species (Capinha et al., 2015). Such a fact means that geographical proximity may have little, if any, implications for the spread of IAS. For instance, our results highlighted that despite the geographical proximity between the Iberian Peninsula and the African continent, not even 8 % of recorded IAS originated from there. In this context, economic interest may play a stronger role than geographical proximity in the distribution of aquatic IAS. For example, Olden et al. (2021) observed that online auctions of living freshwater organisms can link –just a click away– major cities in the United States, Europe and Southeast Asia. Similarly, e-commerce through private-to-private online trading platforms can facilitate the spreading of IAS mainly at national and international scales (Lenda et al., 2014). Moreover, other potentially harmful IAS can be stowed away through the pet trade (Patoka et al., 2016). Hence, both common access routes (ports, harbours, and port facilities) and emerging ones (e-commerce), as well as inter-basin water transfers (common in Iberian Peninsula) or fishing grounds, require special attention when developing aquatic biosecurity procedures and setting up early warning and rapid response protocols.

Ultimately, transboundary communication, cooperation and collaboration are essential to ensure the successful implementation of aquatic IAS management strategies (Caffrey et al., 2014), especially when river basins or water transfer systems are shared among countries. In this sense, we recommend the creation of an Iberian transnational action plan and a common list to act more effectively against aquatic IAS, both those already present in the Iberian Peninsula but also those yet to come. We highlighted the top-priority IAS in Iberian inland waters, thus informing and assisting decision-makers on which IAS management actions are paramount. Despite the enormous effort made in the HS carried out in the Iberian Peninsula, more research is needed to update the lists, and to address other aquatic invasive taxa, including microorganisms or wildlife pathogens other than those affecting livestock, plant crops, and human health, which can cause serious impacts and often go unnoticed (e.g., Roy et al., 2017).

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Data availability

Data will be made available on request.

Declaration of competing interest

Authors declare no conflict of interest.

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