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Research article

Identification of potential invasive alien species in Spain through horizon scanning

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ABSTRACT

Invasive alien species have widespread impacts on native biodiversity and ecosystem services. Since the number of introductions worldwide is continuously rising, it is essential to prevent the entry, establishment and spread of new alien species through a systematic examination of future potential threats. Applying a three-step horizon scanning consensus method, we evaluated non-established alien species that could potentially arrive, establish and cause major ecological impact in Spain within the next 10 years. Overall, we identified 47 species with a very high risk (e.g. *Oreochromis niloticus*, *Popillia japonica*, *Hemidactylus frenatus*, *Crassula helmsii* or *Halophila stipulacea*), 61 with high risk, 93 with moderate risk, and 732 species with low risk. Many of the species categorized as very high or high risk to Spanish biodiversity are either already present in Europe and neighbouring countries or have a long invasive history elsewhere. This study provides an updated list of potential invasive alien species useful for prioritizing efforts and resources against their introduction. Compared to previous horizon scanning exercises in Spain, the current study screens potential invaders from a wider range of terrestrial, freshwater, and marine organisms, and can serve as a basis for more comprehensive risk analyses to improve management and increase the efficiency of the early warning and rapid response framework for invasive alien species. We also stress the usefulness of measuring agreement and consistency as two different properties of the reliability of expert scores, in order to more easily elaborate consensus ranked lists of potential invasive alien species.

1. Introduction

One of the most unique attributes of the Anthropocene is the spread of alien species around the world, due to human activities and the breakdown of biogeographical barriers (Capinha et al., 2015). Such alien species are, in many cases, able to successfully establish themselves in new areas, becoming invasive and acting as one of the most important drivers of change in biodiversity and ecosystem services (Sala et al., 2000; Vilà et al., 2011). Invasive alien species (IAS) can cause widespread habitat alteration, replacement or displacement of native species, transmission of diseases and parasites, hybridization, and negative impacts on human health, and well-being (Diagne et al., 2021; Pimentel et al., 2000; Pyšek et al., 2020). They are of particular concern in insular territories (Bellard et al., 2017). Biological invasions are thus responsible for about 54% of animal extinctions (Clavero and García-Berthou, 2005), and their mean global economic costs are estimated to be more than US$26.8 billion annually (Diagne et al., 2021). In addition, the threat from IAS continues to grow, as the number of introductions worldwide is ever rising, with no sign of saturation (Seebens et al., 2017).

There is consensus on the importance of preventing the introduction of new alien species as the most efficient management tool against IAS (Pyšek et al., 2020). Hence, efforts should be made to determine which alien species may become invasive and cause future environmental and socioeconomic impacts. Once identified, their introduction should be prevented by primarily acting on their entry pathways, and secondarily developing early detection and eradication plans. Horizon scanning (HS) is one way to address this challenge. It involves a systematic review by experts of future threats that species may pose, aiming to prioritize research on potential new IAS that are poorly recognized (Roy et al., 2014; Sutherland et al., 2011). Reporting net economic and ecological benefits, HS is now considered an essential tool for IAS management (Caffrey et al., 2014; Keller et al., 2007). In this context, the procedure consists of building up a list of potential IAS, preparing a simplified assessment of their risks, and reaching expert consensus on a prioritized list of those species (Roy et al., 2014). Horizon scanning is not a risk assessment, as the latter requires an exhaustive bibliographic review of each species and the use of specific mathematical methods or software to quantify the risks (González-Moreno et al., 2019; Vilà et al., 2019). In contrast, HS prioritizes species that actually deserve such risk analyses (Roy et al., 2014). Numerous HS have been performed to identify potential IAS at different spatial scales (see e.g. Dawson et al., 2023; Peyton et al., 2019), analysing different taxa (Gallardo et al., 2016; Roy et al., 2019; Tsiamis et al., 2020). However, approaches to establish lists of potential IAS of national concern that consider a large array of taxonomic groups are rare, despite being essential to underpin policy and management decisions.

Identification of potential IAS can be biased by the personal experience and interests of the experts involved in the HS exercise, and by data availability (Sutherland et al., 2011), given that the lack of impact evidence or invasion history does not imply absence of threat (Roy et al., 2014; Simberloff et al., 2013). Thus, selecting assessors with great expertise, providing clear guidelines, and using explicit measures of reliability can all help to improve consistency and better understand the sources of uncertainty (González-Moreno et al., 2019; Oficialdegui et al., 2023). Previous HS have used different statistics to assess the degree at which experts agreed on their evaluation of species. For instance, Gallardo et al. (2016) used Fleiss' kappa (Fleiss, 1971), while Oficialdegui et al. (2023) used Krippendorff's α (Krippendorff, 2004). Other authors used complementary methods to measure uncertainty, such as requiring the experts to provide the degree of certainty of each score (see e.g. Copp et al., 2009; D'hondt et al., 2015).

Mediterranean countries are important biodiversity hotspots, but also host a significant number of terrestrial, freshwater and marine alien species (Dawson et al., 2017; Drake and Lodge, 2004; Tierno de Figueroa et al., 2013). Spain in particular is a strategic area that connects Europe with Africa and Mediterranean with Atlantic waters, being a key node for preventing the spread of IAS between these regions. Some HS studies have already been conducted in Spain for certain taxonomic groups such as plants (Andreu and Vilà, 2010; Bayón and Vilà, 2019), or ecosystems such as aquatic environments (Oficialdegui et al., 2023; Oliva-Paterna et al., 2021). However, a comprehensive HS analysis for Spain that covers all taxa and ecosystems is lacking. Therefore, our general aim was to perform such an HS analysis for Spain. This was achieved by (1) identifying a list of alien species that are not established in Spain but are likely to arrive, become so and spread, through the evaluation of entry pathways and expected impacts, and (2) measuring agreement and consistency as two different properties of the reliability of individual experts' evaluations. We expect our results will aid in the decision-making needed to implement national and European regulations in Spain.

2. Methods

2.1. Study area

We performed our HS for all Spanish territories, i.e. mainland Spain, the Canary Islands (Atlantic Ocean), the Balearic Islands (Western Mediterranean Sea), and the autonomous cities of Ceuta and Melilla (North Africa), as well as small insular territories in the Mediterranean

Sea and the Atlantic Ocean (Fig. S1). Spain has complex orography and high spatial and temporal climate variability, being the most climatically diverse country in Europe (IGN, 2019). Following the Köppen-Geiger classification, the country includes 13 different climates (IGN, 2019), from hot desert (Bwh) to subarctic (Dfc). Annual mean temperatures range from 2.5 °C in mountainous areas to 22.5 °C in the Canary Islands, while total annual precipitation varies from around 100 mm in the eastern Canaries and Almería to over 2000 mm in Northern Spain (IGN, 2019). Under natural conditions, most Spanish rivers display Mediterranean flow regimes, with a high-flow period during the wet season (i.e. autumn and winter), and a low-flow period during the dry season (i.e. late spring, summer) (Mezger et al., 2021). However, these rivers are highly regulated by more than 1200 large dams (MAPAMA, 2020). Finally, the Spanish marine ecosystems belong to the group known as warm-temperate seas, based on their surface temperatures. These seas show a clear gradient from south to north, ranging from approximately an annual mean temperature of 20 °C in the Canary Islands to less than 12 °C in higher latitudes. There are also marked seasonal temperature variations in the northern half of the studied area, and especially in the Mediterranean, a closed sea that undergoes a significant temperature increase during the summer (AEMET, 2015).

2.2. Horizon scanning protocol

Our HS protocol largely followed Roy et al. (2019), and used an adapted version of the consensus method proposed by Sutherland and Woodroof (2009) and Sutherland et al. (2011) to obtain a ranked list of potential IAS with high biodiversity impact. The protocol involved three main stages: (1) determining the composition and scope of five previously established thematic groups (i.e. marine species, freshwater animals, terrestrial vertebrates, terrestrial invertebrates, and plants; see section 2.2.1.), (2) building a preliminary list of species within each thematic group, performing a rapid evaluation and compiling a preliminary consensus list within groups, and (3) establishing a general consensus and ranked list of potential IAS across thematic groups (Fig. 1 and Table S1 for further details on the protocol and calendar).

2.2.1. Stage 1: composition and scope of the thematic groups

We established five thematic groups, namely: (1) marine, which included all animals, plants and algae from marine habitats; (2) freshwater animals, incorporating aquatic invertebrates that spend most of their life cycle in the water, and fish of freshwater ecosystems and transitional systems such as estuaries or coastal lagoons; (3) terrestrial vertebrates, comprising amphibians, reptiles, birds, and mammals; (4) terrestrial invertebrates; and (5) plants, including terrestrial and aquatic plants from inland waters. We did not consider microorganisms in this study. Each thematic group comprised two co-leaders and four (terrestrial vertebrates) to eight (terrestrial invertebrates) experts—depending on the initial number of species to evaluate (see Table S2)—. This brought together expertise within each group on different taxa and on mainland Spain and island territories. We respected gender parity, also combining the presence of early career and senior researchers in all groups.

2.2.2. Stage 2: preliminary lists of species within each thematic group

Each thematic group started from a potential—but not exhaustive—list of species that we identified using the CABI tool (CABI, 2022). Similarly to Roy et al. (2019), our search criteria selected alien species that: (1) did not have established populations in the study area, (2) present a documented history of invasion and cause undesirable impacts in neighbouring countries to Spain or in other areas worldwide that climatically match the study area (using the Köppen-Geiger climate zones as reference); (3) are traded within the study area or in areas with strong commercial links with Spain or with recognized pathways for their entry; and (4) occur in captivity (e.g. zoological parks, aquaculture facilities and greenhouses) in the study area. Therefore, we excluded

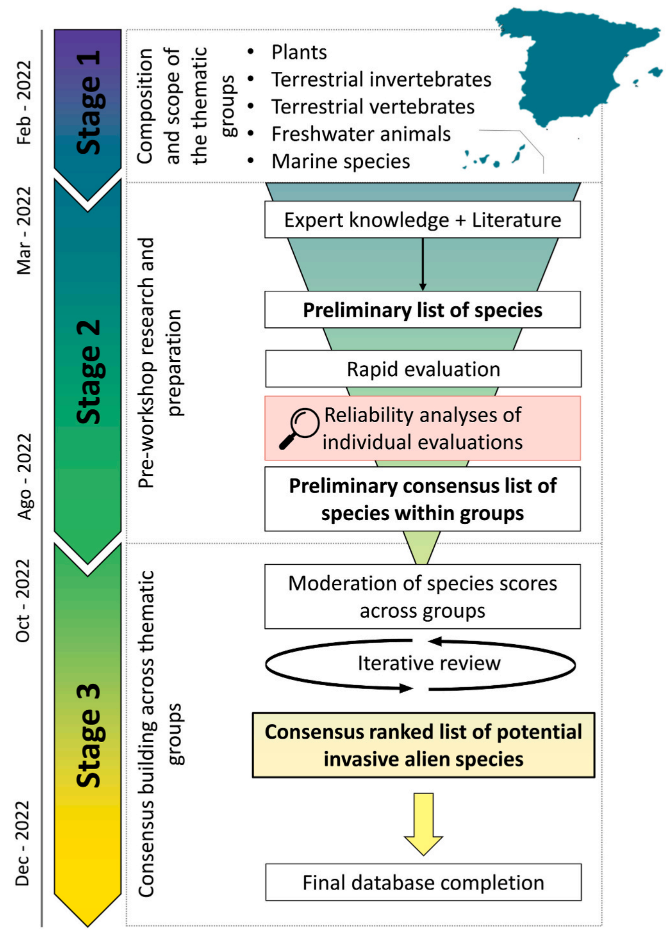

Fig. 1. Horizon scanning protocol used in this study. Based on Roy et al. (2019), it applies the consensus method proposed by Sutherland and Woodroof (2009) and Sutherland et al. (2011).

native species from mainland Spain that could become invasive in insular territories, and *vice versa*.

Due to the very long lists obtained for plants and terrestrial invertebrates (see Table 1), we ranked the species according to their "degree of invasion" (i.e. number of occurrences globally that are considered "invasive") and selected the 200 taxa with a higher degree of invasion. We completed preliminary lists with those species that were included in previous HS conducted in Europe and Spain (Andreu and Vilà, 2010; Bayón and Vilà, 2019; Oficialdegui et al., 2023; Oliva-Paterna et al., 2021; Roy et al., 2014, 2015, 2019), and with those IAS listed in Spanish and European regulations (Law 42/2007, RD 630/2013 and (EU) 1143/2014). Then, experts evaluated the resulting lists over a period of one month, identifying species wrongly included (e.g. native to part of Spain, species complexes or IAS already established; see Table S3 for the complete list of removed species) and/or proposing other potential invasive species for consideration that were not so far included.

Prior to the final workshop, each expert evaluated individually at least 50 species, filling in a spreadsheet template slightly modified from Peyton et al. (2019) (see **Appendix 1**) with scores on their likelihood of arrival, establishment, and impact on biodiversity and ecosystems. These items were scored on a scale of 1 (very unlikely) to 5 (very likely), following criteria established in previous studies (e.g. Blackburn et al., 2014; Peyton et al., 2019) (see Tables S4–S6 for further details). Experts also scored the confidence level of each assignment (Table S7) as low (L, no direct observational evidence available or evidence is difficult to interpret or considered low quality), medium (M, some direct observational evidence is available but may be ambiguous or difficult to scale within the specific geographical context), or high (H, direct

Table 1
Summary of the number of existing, evaluated, and prioritized species within each thematic group. The "Spanish Catalogue of Invasive Alien Species" refers to the Spanish regulation on invasive alien species (Law 42/2007 and RD 630/2013). See text for further details.

Group	Species initially obtained from CABI	Species finally evaluated	Prioritized species with very high/high risk	Species with very high/high risk included in the *Spanish Catalogue of Invasive Alien Species*	Species with very high/high risk included in the list of IAS of Union concern
Marine	56	116	9	1	0
Freshwater	132	182	14	4	2
Terrestrial vertebrates	72	96	31	9	4
Terrestrial invertebrates	5845	267	15	0	0
Plants	628	272	39	3	3
TOTAL	**6733**	**933**	**108**	**17**	**9**

observational evidence is available and straightforward to interpret without controversy and considered to be of high quality) (Blackburn et al., 2014). Similar to Roy et al. (2014), the overall score for each species was calculated as the product of the above mentioned three scores. In sum, the final score for each species assessed by each expert ranged potentially from 1 to 125. Each species was evaluated by 2–5 experts and therefore, received 2–5 final scores.

To assess the agreement and consistency among experts' individual preliminary scores and to facilitate consensus building, we performed two complementary reliability analyses. First, we used Krippendorff's α (Krippendorff, 2004), a standard measure of reliability (Hayes and Krippendorff, 2007) that has proven useful in ecology (e.g. Cano-Barbacil et al., 2020). Krippendorff's α ranges from -1 to 1, with values of 1 indicating perfect agreement, 0 indicating no agreement beyond chance, and -1 indicating inverse agreement (Krippendorff, 2004). Bootstrapped Krippendorff's α and its 95% confidence interval were obtained using the "kripp.boot" function of the R package "kripp.boot" (Proutskova and Gruszczynski, 2017), through the "ordinal" method. We used a beta regression model, run with "betareg" function from the R package "betareg" (Cribari-Neto and Zeileis, 2010; Ferrari and Cribari-Neto, 2004), to test whether there were differences between the agreement of the scores for the different thematic groups and items evaluated. Lastly, we calculated Kendall's coefficient of concordance (W), which is a non-parametric method that also informs about the correlation among experts' scores (Legendre, 2005). To estimate W, we used the "kendallNA" function of the "irrNA" package (Brueckl and Heuer, 2022), which allows for missing values. Note that reliability is used with various meanings in the literature and Krippendorff's α measures higher agreement (i.e. the extent to which different experts tend to assign the same value to each category), whereas Kendall's W measures consistency among experts' scores (i.e. extent to which different experts tend to assign the same relative order to items) (see Table S8 for an illustration). Consistency (often also called reliability) and agreement are different properties of measurement reproducibility that are sometimes unrelated (Bennett et al., 2017; Tinsley and Weiss, 2000). Therefore, we evaluated the relationship between Krippendorff's α and Kendall's W using Spearman's rank correlation. All statistical analyses were carried out using R version 4.2.2 (R Core Team, 2023).

After analysing the agreement and consistency, experts from each thematic group met by videoconference to discuss and modify, when necessary, discrepant scores and to establish a preliminary consensus list for each thematic group based on individual evaluations.

2.2.3. Stage 3: consensus building of the final list across thematic groups

Consensus building among the groups took place during an in-person workshop including joined and separated sessions for thematic groups. In the first session, group leaders presented an overview of their high-ranked species. The experts then had another chance to revise and change their scores in order to moderate scoring approaches among groups, and to include potential new IAS or to exclude those that did not fit the HS criteria (e.g. species recently established). At this stage, the thematic groups were asked to reach a common species score, including confidence levels. In the second session, we combined the lists from the five thematic groups into a single list. Experts were asked to justify their evaluations to ensure a consistent application of scores across all the thematic groups. As a result, we obtained a consensus ranked list of the 933 potential IAS that were considered to represent a very high, high, moderate and low threat to biodiversity and ecosystems in the Spanish territories. The very high threat group included species with the two highest overall scores (125 or 100). Similarly, the high threat group consisted of species with scores of 80 or 75; the moderate threat group, species with scores of 64 or 60; and the low threat group, species with scores below 60.

After the workshop the experts had the chance to review the list, particularly to check the establishment status of each species. We analysed the information retrieved from CABI for each species in order to evaluate the native range, functional group, likely entry pathways and evidence of impact mechanisms of the prioritized species (i.e. those with very high and high risk). We categorized species using published classifications and the terminology of the Convention of Biological Diversity (CABI, 2022; CBD, 2014; Roy et al., 2019) (see Tables S9–S12 for further details). Lastly, we checked the presence of species with very high and high risk in the "Spanish Catalogue of Invasive Alien Species" (RD 630/2013).

3. Results

The preliminary lists compiled 933 alien species with potential to arrive within the next ten years, become established, and have an impact on native biodiversity and ecosystems in the study area. Plants (n = 272), terrestrial invertebrates (n = 267) and freshwater animals (n = 182) had the greatest number of potential IAS, whereas marine (n = 116) and terrestrial vertebrates (n = 96) had the lowest number. On average, terrestrial vertebrates and marine species were evaluated by 3.44 and 3.01 experts, respectively. In comparison, freshwater organisms, invertebrates and plants were assessed by an average of 2.16, 2.04 and 2 experts, respectively.

3.1. Reliability analyses reveal significant concordance among individual evaluations

After conducting the individual risk assessments for each potential IAS, we found that the degree of agreement among experts was significantly different among thematic groups (pseudo-$R^2 = 0.749$, $\varphi = 43.75$, $P = 0.006$), the lowest being for terrestrial vertebrates ($\alpha_{\text{Total}} = 0.226$), and the highest for terrestrial invertebrates ($\alpha_{\text{Total}} = 0.548$) (Fig. 2a and 2**b** and Table S13). We also found significant differences among the different items evaluated. Experts showed higher agreement when evaluating the probability of arrival compared to scoring the probability of establishment and impact of the species (Fig. 2c and Table S13), with the two latter items showing lower confidence levels (Fig. S2). For instance, 50.8% of the evaluations of the probability of arrival showed a

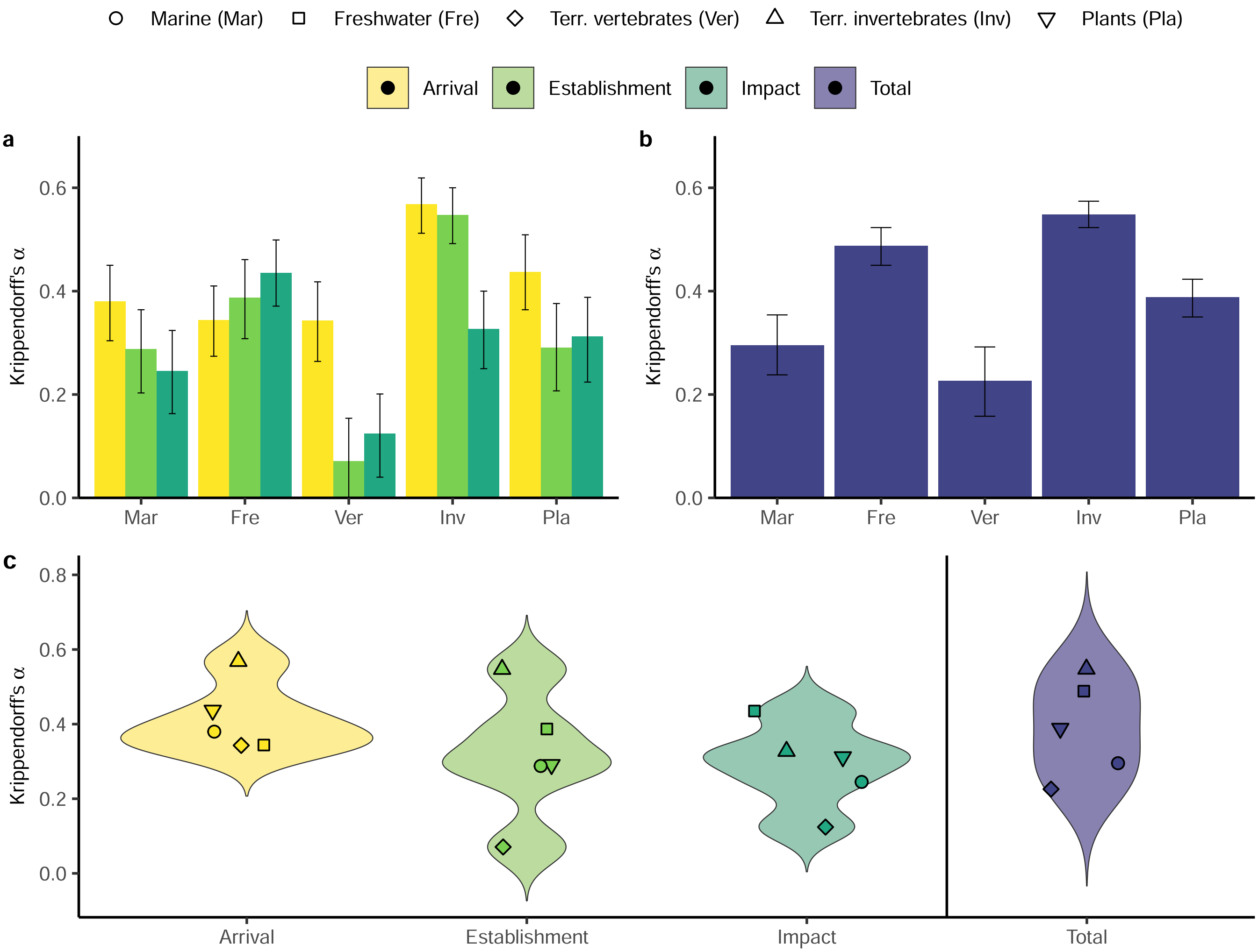

Fig. 2. (a) Agreement among experts (bootstrapped Krippendroff's α and 95% confidence interval) of the three items evaluated (likelihood of arrival, establishment, and impact) by thematic groups during the horizon scanning. (b) Agreement among experts on the total score obtained for each thematic group. (c) Violin graph showing the agreement among experts on the different items evaluated by thematic groups (symbols). Mar = marine species; Fre = freshwater animals; Ver = terrestrial vertebrates; Inv = terrestrial invertebrates; Pla = plants.

high level of confidence, whereas only 39.9% and 25.9% of the evaluations of probability of establishment and impact, respectively, exhibited high confidence levels. Despite obtaining relatively low values with Krippendorff's α, the Kendall coefficients indicate that there was significant consistency in the scores of every item for all thematic groups (Table S14). Conversely, consistency was higher for the arrival of terrestrial invertebrates and freshwater animals, but lower for the establishment and impact of marine organisms and terrestrial vertebrates, although the two measures were significantly correlated (ρ = 0.818, $P < 0.001$; Fig. S3).

3.2. Consensus ranked list of potential invasive species

The final consensus ranked list of potential IAS revealed that 47 species posed a very high risk of arrival, establishment, and ecological impact in Spain (overall scores of 125-100; see Table 2), 61 showed a high risk (80-75), and 93 a moderate risk (64-60) (see Tables S15–S18). The remaining 732 species were categorized as of low risk (<60) (Table S19) and therefore are considered as species with low invasive potential in Spain. The thematic group with the highest number of species classified as very high risk (n = 18) was terrestrial vertebrates (Fig. 3), followed by plants (n = 11), terrestrial invertebrates (n = 8), freshwater animals (n = 7) and marine species (n = 3). Similarly, plants (n = 28) and terrestrial vertebrates (n = 13) were the thematic groups with the highest number of species classified as high risk.

3.2.1. Taxonomic and functional groups of the prioritized species

Irrespectively of the environment, vertebrates (n = 41) and phanerogams (n = 39) together represented 74.2% of the 108 prioritized species (i.e. species with very high and high risk). Arthropods (17 species) were the third group with species classified as having very high and high risk of becoming IAS (Fig. 4a). In terms of functional groups, primary producers were the most represented with 41 species (Fig. 4b), including 39 phanerogams, one green alga and one aquatic fern. Conversely, the least numerous functional group with species with very high or high risk of becoming IAS was filter-feeding species (n = 3). Most terrestrial vertebrates and freshwater animals (86.7%) were predator or omnivorous species, while most terrestrial invertebrates (80%) were herbivorous (Fig. 4b).

3.2.2. Likely native range and entry pathways of the prioritized species

Most of the prioritized species from terrestrial or freshwater ecosystems were native to temperate Asia (37.0%; 40 species) and North America (29.6%; 32 species), with only a small proportion (5.6%) native

Table 2
List of the 47 potential invasive alien species with very high risk of arrival, establishment, and ecological impact in Spain.

Marine (3)	Terrestrial vertebrates (18)	Plants (11)
Halophila stipulacea	*Hemidactylus frenatus*	*Crassula helmsii*
Ulva ohnoi	*Lampropeltis getula*	*Pueraria montana* var. *lobata*
Glycera dibranchiata	*Sciurus carolinensis*	*Cabomba caroliniana*
Freshwater (7)	*Pelophylax lessonae*	*Hydrilla verticillata*
Oreochromis niloticus	*Cynops pyrrhogaster*	*Reynoutria x bohemica*
Pomacea canaliculata	*Rhinella marina*	*Salvinia molesta*
Phoxinus phoxinus	*Ocadia sinensis*	*Sphagneticola trilobata*
Gambusia affinis	*Mauremys (Chinemys) reevesii*	*Miscanthus sinensis*
Dreissena rostriformis bugensis	*Acridotheres tristis*	*Prunus serotina*
Dikerogammarus villosus	*Anser cygnoides*	*Lagarosiphon major*
Procambarus virginalis	*Castor canadensis*	*Ligustrum sinense*
Terrestrial invertebrates (8)	*Osteopilus septentrionalis*	
Popillia japonica	*Macrochelys temminckii*	
Radopholus similis	*Pantherophis guttatus*	
Lissorhoptrus oryzophilus	*Acridotheres cristatellus*	
Orientus ishidae	*Psittacula eupatria*	
Rhagoletis cingulata	*Sternotherus odoratus*	
Aromia bungii	*Trachemys ornata*	
Toumeyella parvicornis		
Argyrotaenia ljungiana		

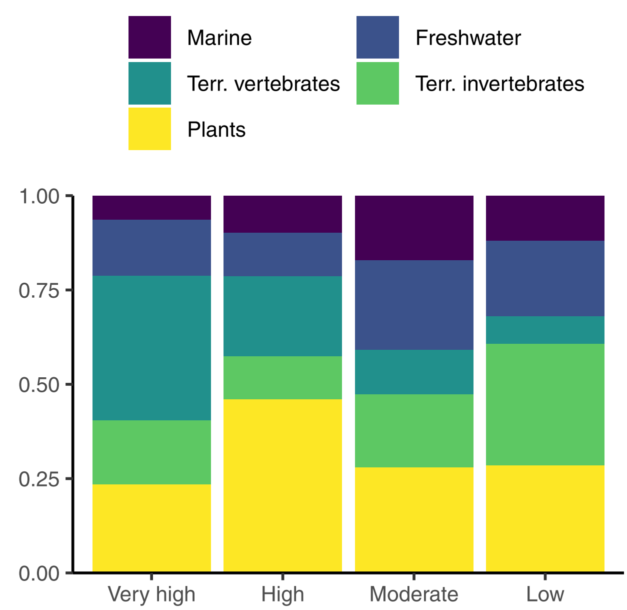

Fig. 3. Proportion of potential invasive alien species that have very high (n = 47), high (n = 61), moderate (n = 93) and low (n = 732) risk of becoming invasive in Spain, based on their likelihood of arrival, establishment and impact on biodiversity and ecosystems.

to Oceania. Among marine species, three were native to the western Indo-Pacific (India, East Africa, and Red Sea), two to the central Indo-Pacific (Philippines, Malaysia, Taiwan, and northern Australia), two to the Northwest Atlantic (eastern USA and Canada) and two to the Northwest Pacific (Japan, Korea, northeast China and eastern Russia) (Fig. 5).

The main entry pathway of the prioritized species (Fig. 5) was escape from confinement (n = 88), followed by stowaway transport (n = 46). However, 66.7% of the prioritized species were polyvectic, i.e. species

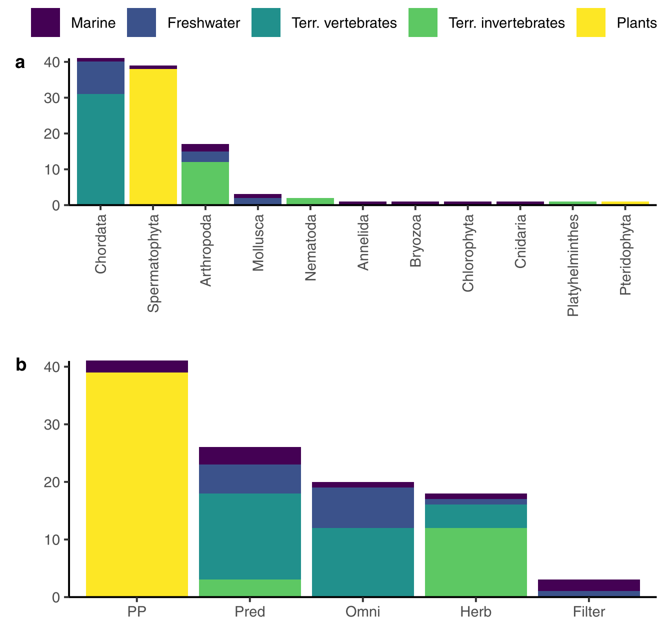

Fig. 4. Number of prioritized species resulting from our horizon scanning for Spain by (a) taxonomic group and (b) functional group. PP = Primary producers; Pred = Predators; Omni = Omnivores; Herb = Herbivores; Filter = Filter feeders.

having two or more known entry pathways. On average, freshwater species had the highest number of known entry pathways per species (mean = 2.71), followed by plants (mean = 2.49), terrestrial vertebrates (mean = 2.20), marine species (mean = 1.67) and terrestrial invertebrates (mean = 1.54).

3.2.3. *Impact mechanisms of the prioritized species*

The main impact mechanism of prioritized species was competition for resources with native species (75.9%; Fig. 6). More than 30% of the prioritized species could also have negative effects on native biodiversity through fast-growing, preying on native species, and/or carrying and transmitting pathogens. On average, freshwater species had the highest number of known impact mechanisms per species (mean = 4.29), followed by plants (mean = 3.03), terrestrial vertebrates (mean = 2.77), marine species (mean = 2.33) and terrestrial invertebrates (mean = 1.60).

4. Discussion

This study represents the first HS analysis conducted in Spain that identifies a list of potential IAS across taxonomic groups and ecosystems. It also highlights the importance of including and correctly using various reliability statistics in HS protocols, in order to measure the agreement and consistency of experts' individual evaluations. Applying these statistics allowed experts involved in this study to identify discrepant scores and produce the consensus ranked list of potential IAS.

4.1. *Prioritized list of potential alien invasive species*

Following the three-step consensus method (Roy et al., 2019; Sutherland et al., 2011), we prioritized 108 species with very high (n = 47) or high (n = 61) risk of becoming invasive in Spanish ecosystems within the next 10 years. Our results are consistent with previous HS, and some of the prioritized species in this exercise were already considered as potentially having very high risk for Spanish ecosystems in previous studies (e.g. Amur sleeper (*Percottus glenii*), *Procambarus*

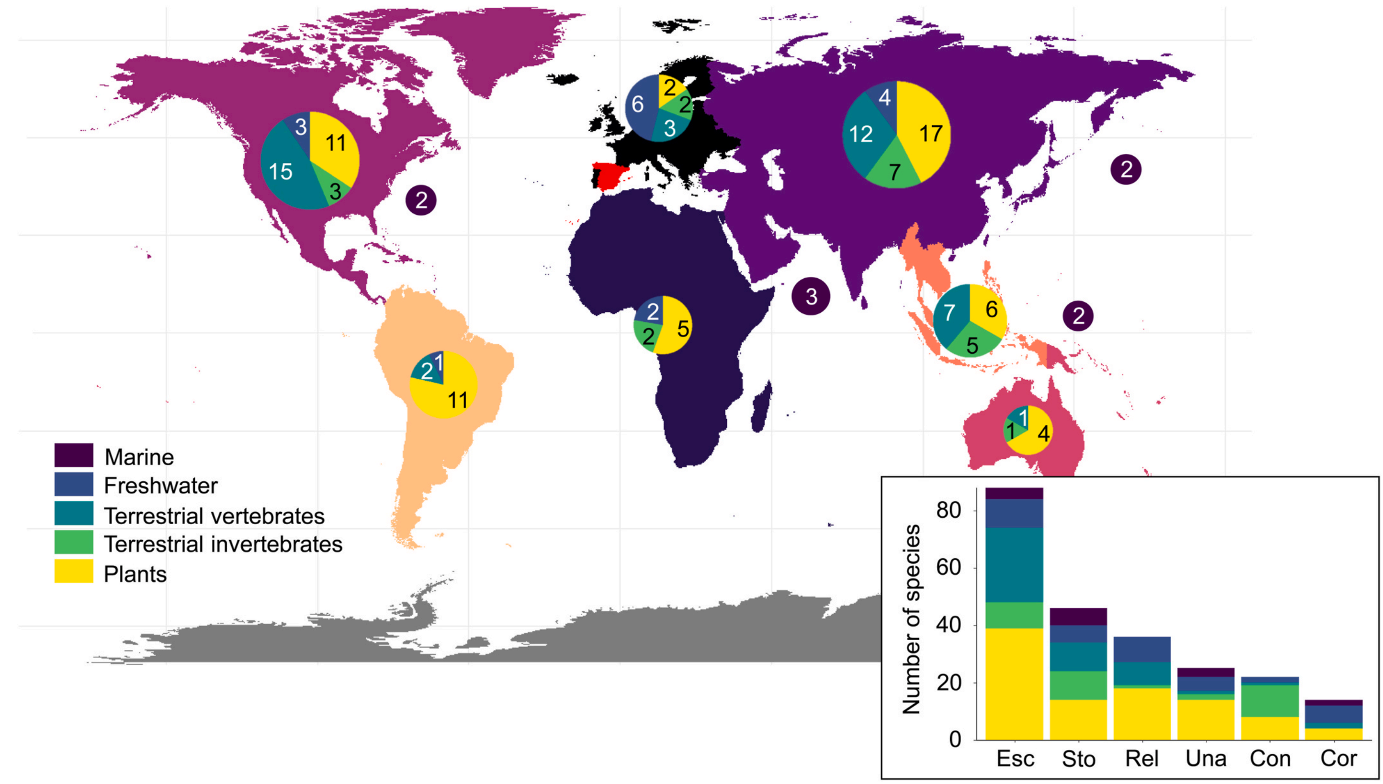

Fig. 5. Native range of prioritized species resulting from our horizon scanning for Spain. The number of species for each thematic group is indicated in the pie charts, the size of which is proportional to the total number of species. Note that some species are native to more than one region, and therefore, the sum of all species is not equal to 108 (total number of prioritized species). The study area is highlighted in red. The bar graph at the bottom classifies the main entry pathways of prioritized species (Esc = Escape; Sto = Stowaway; Rel = Release; Una = Unaided; Con = Contaminant; Cor = Corridor). Note that species may have more than one known or potential entry pathway.

virginalis or *Crassula helmsii*) (Andreu and Vilà, 2010; Oficialdegui et al., 2023). Many of these prioritized species are already present in Europe and neighbouring countries to Spain. This is the case, for example, of the grey squirrel (*Sciurus carolinensis*), which is native to deciduous forests in the USA and is considered invasive in the UK, Ireland and Italy (Lowe et al., 2000), or the Amur sleeper, which is one of the most widespread and successful invaders in European inland waters (Copp et al., 2005; Reshetnikov, 2010). Some prioritized species, such as *Salvinia molesta* or *C. helmsii*, the Chinese turtle (*Mauremys reevesii*), or *P. virginalis* (found in Asturias –northern Spain– for the first time during this study) are species that have already been detected locally, although not yet established in Spain (de la Vega et al., 2021; MAGRAMA, 2013a; Salas-Pascual and Quintana Vega, 2016). Similarly, while this manuscript was being prepared for submission, Png-Gonzalez et al. (2023) updated the list of marine aliens in Spain, showing that actually *Schizoporella japonica*, which we identified as high concern, is already considered a casual alien species in Spain, which reinforces the robustness of our HS exercise. *Ulva ohnoi* and *Penaeus monodon* were also included in this list, however their current status in the study area is unknown. As for the remaining species that were found to have a moderate or low impact, it is important to note that the absence of impact evidence or invasion history in many cases does not necessarily imply the lack of existing or future impacts (Simberloff et al., 2013). Therefore, based on the precautionary principle, prevention is key to managing the environmental challenge of invasive species.

Most of the prioritized species have a long invasive history and are very frequent in the pet trade, for example the common house gecko (*Hemidactylus frenatus*) or the Chinese turtle (see e.g. de la Vega et al., 2021). Twelve very high or high risk IAS are included in the list of the "100 of the World's Worst Invasive Alien Species" (Lowe et al., 2000): *Sciurus carolinensis, Pueraria montana* var. *lobata, S. molesta, Pomacea canaliculata, Rhinella marina, Acridotheres tristis, Sphagneticola trilobata, Gambusia affinis, Platydemus manokwari, Prosopis glandulosa, Herpestes auropunctatus,* and *Boiga irregularis*. However, 84.3% of the 108 alien species prioritized in this study are not included in the "Spanish Catalogue of Invasive Alien Species" (RD 630/2013). In the specific case of terrestrial invertebrates, none of the 15 prioritized species are included in this legislation. Thus, given that one of the objectives of this study is to prevent the most potentially harmful IAS from colonizing and damaging Spanish biodiversity and ecosystems, we propose to carry out a more exhaustive risk analysis focused on those species.

Marine taxa were poorly represented in the prioritized species list compared to other groups, despite European seas being one of the most important invasion hotspots worldwide (Tsiamis et al., 2018) and recent studies showing the importance of the Spanish coasts for the establishment of new IAS (González-Ortegón et al., 2020; Zamora-Marín et al., 2023). This pattern was also observed in previous HS (Roy et al., 2014, 2019) and even in the list of species of concern of the European Union IAS Regulation, which includes only two marine/brackish species (*Eriocheir sinensis* and *Rugulopteryx okamurae*). This limited coverage of marine taxa in the current and previous exercises indicates a lack of information on biological invasions in marine habitats (Giakoumi et al., 2016; Occhipinti-Ambrogi and Savini, 2003). However, the thematic group least represented in the prioritized species list in relative terms (i.e. number of taxa included per estimated total number of species) was terrestrial invertebrates. The lack of information and expertise in some taxonomic groups has been identified as a major reason for the difficulty in covering all marine species and terrestrial invertebrates with the same level of precision (Roques et al., 2008). This lack of knowledge can lead to underestimating the invasive potential of these species, unless they are economic pests, pathogen vectors or phytosanitary threats (Roques et al., 2008). Moreover, marine species and terrestrial invertebrates

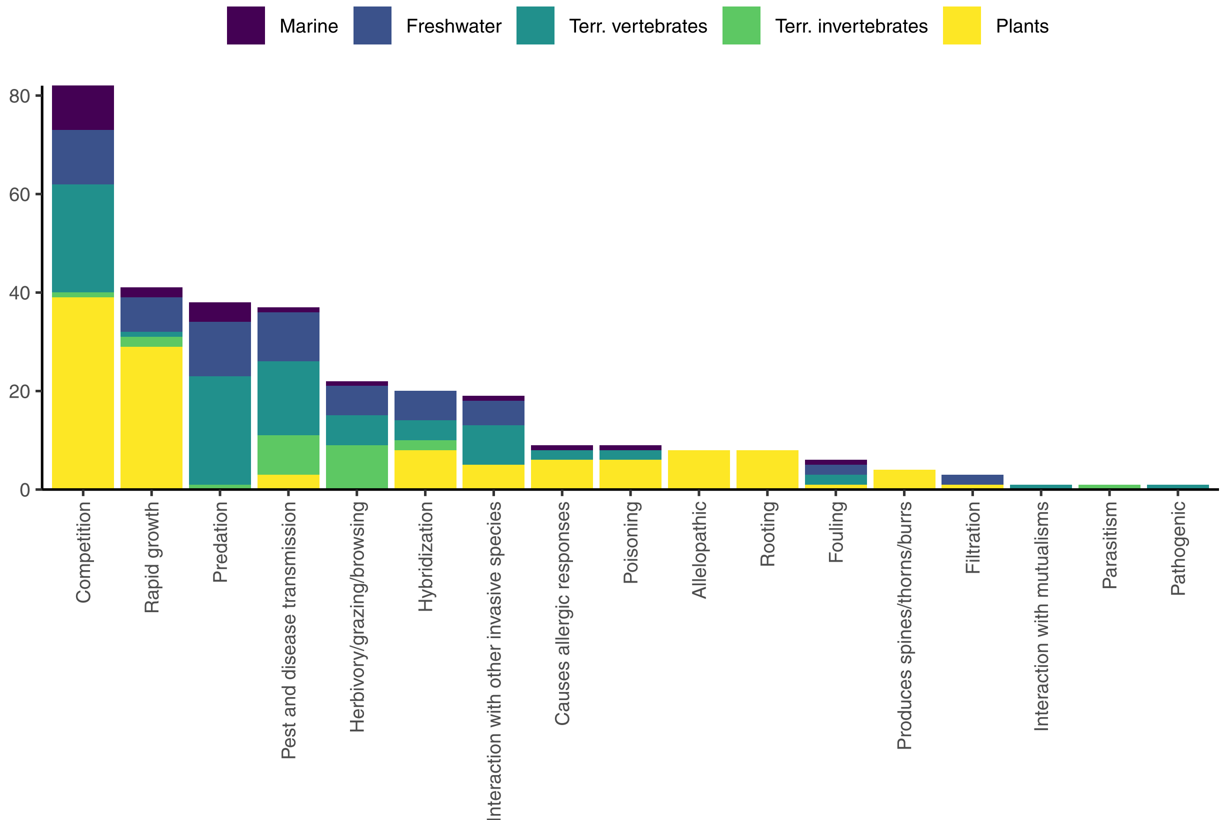

Fig. 6. Number of prioritized species resulting from our horizon scanning for Spain that can cause an impact on native biodiversity and ecosystems through the different mechanisms evaluated. Note that species may have an impact on biodiversity through several mechanisms.

were the thematic groups with the lowest number of known introduction pathways and impact mechanisms per species, so further research on these taxa and ecosystems is urgently needed (Roques et al., 2008; Tsiamis et al., 2020).

Introductions from Asia and North America are likely to be more common compared to other regions, as also indicated by other studies carried out in Europe (Gallardo et al., 2016; Roy et al., 2019; Seebens et al., 2015; Zieritz et al., 2017) and Spain (Bayón and Vilà, 2019; Oficialdegui et al., 2023). This suggests that mechanisms involving long distance transport can play an important role in the entry of potential IAS, which is also corroborated by recent inventories of IAS established in Spain (e.g. Muñoz-Mas and García-Berthou, 2020; Zamora-Marín et al., 2023). However, escape from confinement was considered the most likely route of entry, especially for plants and terrestrial vertebrates. This pattern is consistent with already established European IAS (DAISIE, 2009) and with previous HS at the European level (Roy et al., 2019). In fact, most alien plants are expected to arrive as escaped ornamental or horticultural plants. Similarly, many alien terrestrial vertebrates are expected to arrive as escaped pets or escapes from farms and zoos (Hulme et al., 2008; Saul et al., 2017). By contrast, for terrestrial invertebrates and marine species, transport prevails as entry pathway (stowaway and contaminant categories) (Hulme et al., 2008; Saul et al., 2017). Indeed, these unintentional introductions via contaminant, stowaway, corridor and unaided pathways have increased in prevalence among species introductions over recent decades (Zieritz et al., 2017). Importantly, the spread of potentially invasive species from neighbouring regions is expected to be the third most important donor of IAS. We found that most of the prioritized species are polyvectic, which complicates the possibility of preventing their introduction or tracing their invasion trajectory (Ulman et al., 2017).

In agreement with previous analyses, competition, rapid growth, and predation were reported as the main impact mechanisms of potential invasive species (Roy et al., 2019). However, the magnitude of these impacts can differ between islands and continental territories (Dueñas et al., 2018). Predation by vertebrates is considered one of the main impact mechanisms, especially on islands, and is a major threat to native birds, mammals, and reptiles (Doherty et al., 2016). In contrast, competition is not an impact mechanism likely to cause species extinctions or extirpations in the short term (Davis, 2003; but see Hernández-Brito et al., 2014), although it can cause major changes in community composition and diversity (Kumschick et al., 2015).

4.2. The particular cases of the Balearic and Canary Islands

Insular territories are particularly vulnerable to biological invasions as many native species have evolved in isolation and, therefore, some of them have lost their ability to evade predators, defend themselves from pathogens and parasites, or compete with other species (Bellard et al., 2017; Simberloff, 1995). In particular, it is well known that invasive species are one of the main factors threatening endangered species in the Balearic and Canary archipelagos (see Nogales et al., 2006; Riera et al., 2002; Traveset et al., 2009). Additionally, both the Mediterranean and Macaronesian biogeographic regions are expected to be the most threatened by alien species (Roy et al., 2019). Thus, identifying potential invasive species in these archipelagos is fundamental to prevent future invasions and prioritize management efforts.

Some of the prioritized species could cause a particularly important impact on Spanish islands and their surroundings seas, according to the expert assessment and literature (Table S20). For instance, the small Indian mongoose (*H. auropunctatus*) is considered one of the 100 most harmful IAS and is known to cause the extirpation and extinction of native birds, reptiles and amphibians on other islands (Barun et al., 2011). In fact, the scope of Spanish regulations for some of the prioritized taxa is limited to insular territories only (e.g. species of the

Colubridae family, *Lampropeltis getula*, *B. irregularis,* and *Pantherophis guttatus*). Lastly, it is worth mentioning that some species have already been cited in the archipelagos, although there is no evidence that they have become established in the wild. This is the case of the apple snail (*P. canaliculata*), found in the Ayagaures reservoir in Gran Canaria (MAGRAMA, 2013b). The common myna (*A. tristis*), until recently a fairly common cage species, was introduced into the Balearic and Canary Islands after the escape of some birds that were able to breed in urban and rural environments on Gran Canaria, Tenerife, and La Palma. This species has also been seen in the wild in Fuerteventura, Lanzarote, and Mallorca (Lorenzo, 2007). To date, it has been eradicated from both archipelagos (Saavedra Cruz and Reynolds, 2019). The common myna can cause serious damage to the islands' fauna, as it competes with small mammals and other birds for nesting spaces, and is capable of feeding on the eggs and chicks of other species. Furthermore, there are reports of a still localized presence of three plant species: *S. molesta*, a water fern recently cited for Gran Canaria in artificial habitats; *Casuarina equisetifolia*, present in the Canary Islands for some time, but very localized, and *Passiflora suberosa,* cited for La Palma (Gobierno de Canarias, 2023; Salas-Pascual and Quintana Vega, 2016). Some individuals of the mosquito *Aedes aegypti,* which is the main vector of arboviruses such as yellow fever and dengue, were also detected in the Canary Islands in 2022, although the species is not established (Ministerio de Sanidad, 2022).

The Canary Islands are also at high risk of introduction and establishment of tropical or subtropical marine species, and the shallow waters around the archipelago could be stepping stones for East and West Atlantic warmwater species. Furthermore, the Macaronesia region serves as an important hub for the transportation of oil platforms from several locations around the world, causing a remarkable number of new introductions (Castro et al., 2022; Png-Gonzalez et al., 2023). Species such as *S. japonica* or *Pterois miles* could be introduced by this pathway (Castro et al., 2022; Nuttall et al., 2014). Moreover, the case of *Glycera dibranchiata* has already been studied in Canarias (MITECO, 2017). This species is frequently used as live bait and the impact of its accidental introduction could lead to competitive displacement or predation of native species, since there are several similar species on these coasts from the family Glyceridae.

It is important to note that this study has not included native species from other areas of Spain that could become invasive in the Balearic and Canary archipelagos, causing a great impact. For instance, *Pelophylax saharicus,* finally excluded from this study as it is native to Ceuta and Melilla, has already been cited in the Canary Islands as invasive. Therefore, it would be advisable in the near future to carry out specific horizon scanning for the Balearic and Canary archipelagos.

4.3. Reliability of individual evaluations: a new step for the horizon scanning protocol

Estimation of the invasive potential of alien species can be influenced by the personal research experience and interests of the experts involved in the exercise, as well as by data availability (Sutherland et al., 2011). For this reason, previous studies have already pointed out the usefulness of applying specific measures of reliability to better understand these sources of uncertainty (Gallardo et al., 2016; Oficialdegui et al., 2023). As far as we know, this study is the first using two complementary statistics in HS of alien species to evaluate the agreement and consistency of experts' evaluations. Calculating these specific measures of reliability allowed experts to identify and reduce the impact of sources of uncertainty, and to establish consensus scores. We found that individual scores on the likelihood of arrival, establishment and impact on biodiversity and ecosystems prior to the workshop showed significant consistency within all the groups of experts. This indicates that experts tended to assign the same relative scores to the evaluated items. These results concord with previous assessments of invasive species, which in general showed high consistency on impacts among experts (Bernardo-Madrid et al., 2022). However, we found that the degree of agreement in evaluations was significantly different between items. Lower levels of agreement were observed for those items where experts also had lower confidence levels. This could be due in part to the greater uncertainty in evaluating the likelihood of establishment and impact than the likelihood of arrival, as little information is available and it is difficult to predict potential impacts by extrapolating from other territories (Elliott-Graves, 2016; McGeoch et al., 2012). We also observed that consistency and agreement were correlated, despite providing different information, a finding rarely acknowledged in the literature (Bennett et al., 2017; Tinsley and Weiss, 2000). The two reliability measures were correlated, however they responded differently in our study. Although Krippendorff's alpha has been emphasized in previous ecological studies (e.g. Cano-Barbacil et al., 2020; Oficialdegui et al., 2023), the example in Table S8 shows that consistency statistics can be even more informative in ranking exercises.

5. Conclusions

There is a pressing need to improve evidence-based assessments of the IAS risks to prioritize actions in several geographical regions and countries. Although HS uses expert judgment to extrapolate complex processes such as the likelihood of establishment or the impact of species in a new area, usually from incomplete evidence, several previous exercises have been successful in predicting alien species introductions (Roy et al., 2014, 2019). The present HS strengthens IAS policies in many ways, including improved regulation, justification of trade restrictions and monitoring surveillance procedures. Compared to previous HS in Spain, our analysis screens potential invaders from a wider range of terrestrial, freshwater and marine organisms. This allows us not only to update the list of potential IAS that deserve prioritizing management efforts and resources, but also to identify species that merit more exhaustive risk analyses. Our results also support the convenience to include reliability analyses in HS protocols for IAS. The use of agreement and consistency statistics can help identify sources of uncertainty, and catalyse the consensus building of a final list across thematic groups.

Credit author statement

Leaders of thematic groups devised the study. CCB prepared the preliminary list of species and compiled the data. All authors evaluated potential invasive species. Statistical analyses were carried out by CCB with specific assistance from EGB. CCB wrote the original draft, and all authors commented on and contributed to revising the draft versions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118696.

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