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Management of invasive alien species in Spain: A bibliometric review

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Abstract

Scientific and grey literature on invasive alien species (IAS) is conditioned by social, economic and political priorities, editorial preferences and species and ecosystem characteristics. This leads to knowledge gaps and mismatches between scientific research interests and management needs. We reviewed the literature on IAS management in Spain found in Scopus, Web of Science, Google Scholar and Dialnet to identify key deficiencies and priority research areas. The collected literature was classified, employing features describing formal aspects and content. We used bibliometric and keyword co-occurrence network analyses to assess the relationship between features and reveal the existence of additional topics. Most of the compiled documents (n = 388) were focused on terrestrial ecosystems and inland waters, whereas marine and urban ecosystems were under-represented. The literature was largely generic and not species-specific, focusing on raising awareness and proposing changes on current regulation as prominent approaches to prevent further introductions. The compiled authors exhibited many clear publishing preferences (e.g. language or document type), but less regarding target taxa. In addition, there was a strong association between species and the different features considered, especially between the methodological approach (e.g. review, field experiment) and the primary emphasis of study (i.e. basic/theoretical, applied or interdisciplinary). This indicates that research on IAS has had a strong species-specific focus. References about terrestrial species focused mainly on vascular plants, whereas references about inland waters were mostly on fishes and the giant reed (*Arundo donax*), which has been managed with partial success. Animal culling and plant removal were the most frequent eradication and small-scale control treatments, whereas the documents addressing wider spatial scales were largely theoretical. Consequently, the success of described treatments was largely uncertain. Spanish invasion science research has been occasionally innovative, incorporating novel technologies (e.g. species distribution modelling) and engaging society with citizen-science approaches. However, the ratio between basic/theoretical and applied studies indicates that more applied research/management is needed, especially in inland waters and marine ecosystems. We call for increasing effort in the effective dissemination of experience in IAS management to enhance current practical knowledge, including that of schemes undertaken by public agencies.

Keywords
Biological invasions, eradication, control, Iberian Peninsula, Mediterranean, Spanish archipelagos, keyword co-occurrence analysis, prevention

Introduction

Biological invasions are human-assisted global phenomena with ravaging effects, not only on biodiversity and ecosystem services, but also on human well-being (McGeoch et al. 2010; Vilà and Hulme 2017). Although transport and introduction of alien species into novel ecosystems is inherent to humankind's expansion (Crees and Turvey 2015), the number of new introductions has increased exponentially since the mid-twentieth century (Seebens et al. 2018, 2019). Invasive alien species (IAS) can reshape ecosystem processes, decrease native species richness and abundance (e.g. McGeoch et al. 2010 and references therein) and cause impact on the economy and human health (Zenni et al. 2021). Thus, preventative, eradication and control actions are required to impede their entry and establishment or minimise their long-term impacts (Robertson et al. 2020).

The incidence of biological invasions and their related costs have led to substantial management efforts worldwide to prevent new introductions and control those already established, by means of eradication or containment (García-de-Lomas and Vilà 2015; Diagne et al. 2021). However, to offer efficient responses is challenging and, regrettably, the specific literature on IAS management is often neglected during the decision-making process (Walsh et al. 2015). In Spain, managers, consultants and assessors face obstacles to find and access suitable references, as a large proportion of papers are written in English, are too scientifically orientated or narrowly focused to be directly applied or are not open-access (Andreu and Vilà 2007; Mungi et al. 2019; Copp et al. 2021). In addition, many applied studies are scattered amongst the grey literature (often in many different languages), tending to be largely inaccessible to international readers, which further limits the transfer of knowledge on both local and international levels (Haddaway and Bayliss 2015, Jeschke et al. 2019).

In addition to accessibility barriers, the content of scientific literature is also taxonomically and geographically biased (Hulme et al. 2013). This is accentuated by the fact that reviews and positive rather than negative results are more likely to be published (Fanelli 2012). Thus, several characteristics inherent to IAS and recipient ecosystems utterly favour the availability of literature on specific taxa, regions or ecosystems that are easier to study and/or manage (Thomsen et al. 2014; Nghiem et al. 2016; Shackleton et al. 2019). Moreover, trends in invasion science are also affected by social and political priorities, which are, in turn, influenced by communication media and the outcomes of previous research (Gläser and Laudel 2016; Geraldi et al. 2019; Shackleton et al. 2019). This can lead to changes in the importance of research topics over time, for instance through fostering a given species over others or by abandoning certain research areas.

Bibliometric and keyword co-occurrence network analyses are useful to reveal the main knowledge components of any discipline, such as areas with deep insights, outstanding gaps and peripheral research areas (Aria and Cuccurullo 2017, Radhakrishnan et al. 2017). Despite some recent contributions (Enders et al. 2019, 2020), such analyses are scarce in previous reviews of IAS literature, particularly related to management. Consequently, we chose to use them to identify the main patterns in the scientific literature shown by IAS management in Spain. Our specific aims were to: (i) characterise the species, topics and approaches from a management viewpoint, (ii) detect relationships between them and (iii) identify research areas deserving further attention. We focused on Spain due to its diversity of climates and ecosystems, along with its insular and continental territories, which have favoured the establishment of a large and diverse number of IAS (Muñoz-Mas and García-Berthou 2020). Mainland Spain is part of the Mediterranean biodiversity hotspot (Williams et al. 2011) and encompasses an enormous range of ecosystem types, from arid coastal regions to mountain ranges and woodlands. Spain includes two markedly-different populated archipelagos: the Mediterranean Balearic Islands and the Macaronesian Canary Islands off the north-western African coast (Andreu et al. 2009; Benito-Calvo et al. 2009). Islands are in themselves biodiversity hotspots, but they have especially suffered from the establishment of IAS, which have caused numerous extinctions (Lenzner et al. 2020). In addition, Spain has two autonomous cities located on the Mediterranean coast of the African continent, which may require different IAS management approaches. Former reviews on invasion management in the country were sectorial and focused on stakeholder perceptions and management of alien plants (Andreu et al. 2009) or were based on the most common deficiencies in IAS management (Dana et al. 2019). Thus, reviewing past and present experience may help to improve current IAS management actions and identify future research lines in Spain and similar territories. Our results may help funding agencies to target as yet unidentified research needs.

Methods

Literature review

We performed our literature search using Scopus, Web of Science (WoS) and Google Scholar. The first two mainly focus on English language literature, largely scientific papers, whereas the references compiled within Google Scholar are more heterogeneous and less structured (Haddaway et al. 2015). Monolingual searches have been shown to limit and bias results in global literature reviews (Angulo et al. 2021; Nuñez and Amano 2021). To avoid such potential bias, in addition to Google Scholar, we also consulted Dialnet. This is a multidisciplinary reference database launched in 2001 that focuses on scientific literature published in Spanish, including books, theses and other documents.

We used the following search terms in Scopus and WoS (both accessed 28 April 2020): (Spain OR Iberian Peninsula OR Canary Islands OR Balearic Islands OR Ceuta OR Melilla) AND (alien species OR exotic species OR non-native species OR invasive species OR introduced species OR species introduction OR translocated species OR species translocation OR species spread OR naturalised species OR casual species OR species of concern OR noxious species OR pernicious species OR harmful species) (Rytwinski et al. 2020). We also used the equivalent Spanish terms for searches in Google Scholar and Dialnet, the latter accessed 30 May 2020. The results were downloaded from Scopus, WoS and Dialnet and duplicates removed (Rytwinski et al. 2020) (Table 1). Following Rytwinski et al. (2020), we modified this general workflow for searches in Google Scholar to deal with the inferior specificity of the searching engine. Between 29 April and 30 May 2020, we retrieved up to 1,000 documents, including duplicates, starting the search using the Spanish keywords describing the toponymy (e.g. España or peninsula Ibérica) and terms used to name IAS (e.g. especie exotica or especie invasora) with one of the following terms: gestión (management), erradicación (eradication) or control. Starting with gestión, we selected documents up to the point when they were clearly irrelevant or duplicated. We then repeated the query using the following keyword (first erradicación and finally control) and repeated the entire process using the English keywords. Once 1,000 documents were compiled, the full text was checked to discard irrelevant documents and, only then, we added the document to the references obtained from Scopus and WoS (Table 1).

Only documents focusing on direct IAS management (i.e. eradication and control) or with explicit management implications in Spain were included (e.g. risk assessment and prevention of future invasions, regulations or education). Studies exclusively focusing on the biology or the ecology of IAS, with no management implications or with no examples, were discarded. We only counted introduced and established species or species able to spread in the wild (e.g. Blackburn et al. 2011), excluding those in captivity or cultivated. We also considered microorganisms and parasites (potentially) affecting other species in the wild (e.g. the crayfish plague *Aphanomyces astaci* or the amphibian chytrid fungus *Batrachochytrium dendrobatidis*), but excluding agricultural pests or pathogens of captive animals or humans.

In general, no agriculture-related studies were retained, nor weeds interfering with crops or plantations. However, studies on the red weevil, *Rhynchophorus ferrugineus*, were not excluded, although they focused on the date palm *Phoenix dactylifera*, because this weevil also affects the endemic Canary Islands date palm *Phoenix canariensis*. We compiled a total of 388 documents (Table 1).

Literature characterisation and keyword compilation

We selected relevant features of the retrieved documents for our analysis, following previous bibliographic studies on IAS management (mostly Bayliss et al. 2013; Matzek et al. 2014) (Table 2). The selected features described formal aspects (e.g.

Table 1. Total number of references retrieved before scrutiny (e.g. including duplicates) and final number of references retained for the database. Web of Science and Scopus were managed simultaneously because they show a great overlap of hosted references.

Bibliographic database	Number of references retrieved	Number of references retained
Scopus	1569	214
Web of Science	1152	
Dialnet	75	62
Google Scholar	1000	112

Table 2. Features and categories used to characterise the compiled literature (based on Andreu and Vilà 2007; Bayliss et al. 2013; Matzek et al. 2014). Specific definitions for each category of the selected features are provided in Supplementary Material (Table S1).

Feature	Categories
Authors	–
Document type	Scientific article, book, book chapter, conference proceedings, report or thesis
Ecological organisation level	Population/autoecology, community/assemblage, ecosystem or generic/not applicable
Ecosystem type	Terrestrial, inland waters, marine or urban
Insular territory	Yes or no
Language	English or Spanish
Main topic	Management (eradication and control), prediction, prevention, prioritisation (including risk management), regulation/decision-making, risk assessment, social, biology/ecology, climate change and other synergisms, conservation, definitions, economics, education and awareness-raising, impacts, information sharing, communication and collaboration, introduction/spread or survey/monitoring
Management topic	Prevention, eradication, control or generic/not applicable
Methodological approach	Review/meta-analysis, observational field study, field experiment, greenhouse/laboratory experiment, opinion paper or theory
Primary emphasis	Basic (without direct manipulation of the target taxa), applied (with direct manipulation of the target taxa) or interdisciplinary (encompassing social and policy issues)
Protected area	Yes or no
Spatial scale	Local, regional, national, supranational/global or other/undefined (e.g. greenhouse/lab experiment)
Species	Target species, taxon or generic/multiple taxa
Success	Yes, partial, no, unknown or not applicable
Treatment	Regulation, awareness raising, culling, biocontrol agent, poisoning, hydrology manipulation, hydrogeomorphological restoration, survey and monitoring, mechanical removal, manual removal, herbicide, genetic selection, exclosure, not applicable, DNA metabarcoding, re-afforestation, heating, baiting, containment, mulching, prevention, restocking, incineration, insecticide or sterilisation
Year	-

document type or text language) and content (e.g. methodological approach, main topic, spatial scale). To better characterise documents with multiple topics and sections, the categories within the different features were non-exclusive. That is, a document could focus on the biology/ecology, introduction/spread and survey/monitoring of IAS or on prevention, eradication and control. However, during subsequent analyses, we downweighed each reference in the frequency-related calculations to sum up to one and ensure the equal contribution of all documents (Muñoz-Mas and García-Berthou 2020).

We downloaded the keywords from documents retrieved from Scopus and WoS and manually scrutinised those documents compiled from Google Scholar and Dialnet to compile the available keywords. Then, we inspected the keywords to detect mistakes and misspellings and translated those words into Spanish using Google Translator, adjusting English keywords to well-established terms when necessary (e.g. caña común/common reed to giant reed). The references and features can be found in Supplementary Material.

Data analyses

We used the cumulative sum of number of documents per year to compare the publishing trends in management of invasive alien species in Spain with more general science publishing trends (in Spain and worldwide). The total number of documents published worldwide and in Spain were those included in the Journal Citation Reports (JCRs). The series were retrieved from: www.scimagojr.com/countryrank.php. Frequency bar plots enabled scrutiny of the prevalence of the different categories of each additional feature, except species and ecosystem types. We investigated these two features simultaneously using the function comparison.cloud of the R (R Core Team 2021) package wordcloud (Fellows 2018), but without graphical scrutiny for language, insular territory or protected area, due to their binary nature.

The association amongst features was analysed, except year (Table 2), employing Cramér's V Index (Cramér 1946), implemented in the R package oii (Hale et al. 2017). This Index ranges from 0 (no association) to 1 (perfect association) and is based on a corrected χ^2 statistic. To graphically describe the association patterns, we built a network using the R package igraph (Csardi and Nepusz 2006), employing the values of the Index only when statistically significant ($P < 0.05$).

Cramér's V Index evaluates the association between features, but provides no information about the relationship amongst categories. Therefore, we built two alluvial diagrams to graphically scrutinise the relationship between the categories of the features: methodological approach, ecosystem type, management topic and spatial scale and ecosystem type, treatment and success (Table 2). Alluvial diagrams are a kind of Sankey diagram that group together observations of the same category and visualise them as flows across the considered set of features (Rosvall and Bergstrom 2010). We used the function SankeyDiagram in the R package flipPlots (Displayr 2019) to build the alluvial diagram.

To investigate the existence of additional topics and research areas not described by the features and categories detailed in Table 2, we analysed the literature using a keyword co-occurrence network (Radhakrishnan et al. 2017). As customary, we first systematically lemmatised/stemmed the resulting keywords in R (i.e. inflected or derived words were reduced to their root form) to reduce the variability within the collected keywords. For example, by applying this procedure, the word biolog would result from the words biological and biology. For this, we used the function wordStem of the R package SnowballC (Bouchet-Valat 2020) to allow reproducible results. Compound keywords were split (e.g. invasive species was divided into invasive and species), each word was lemmatised independently (e.g. invas and speci) and the resulting words were reassembled (e.g. invas speci) to build the co-occurrence network. The co-occurrence matrix cross-product was obtained via the function cocMatrix of the R package bibliometrix (Aria and Cuccurullo 2017) and we built the co-occurrence network with igraph (Csardi and Nepusz 2006). We delineated the relevant research areas or clusters employing the function cluster_edge_betweenness (Newman and Girvan 2004) in igraph (Csardi and Nepusz 2006). Finally, the most frequent keyword of each cluster was used to simplify the complete network into a smaller network and facilitate its interpretation. To avoid oversimplification of the network, we kept the most frequent keywords (> Q_{95} or number of occurrences ≥ 4 occurrences), while the less frequent keywords were collapsed to the most frequent keyword in the corresponding research area (i.e. the cluster centre). We depicted the resulting network with the most important keywords in each research area (i.e. cluster centres encompassing the most frequent and less frequent keywords into single vertices and additionally those keywords whose frequency of occurrence was ≥ 4) as two-level circular treemaps (Zhao and Lu 2015) using the R package ggraph (Pedersen 2021).

Results

The number of documents published on IAS management has grown steadily since 1995 (Figure 1A). However, those published in Spain are under-represented compared to the scientific production trends both globally and in Spain, although during the last decade, the scientific production accelerated significantly. Most documents were scientific articles (72.4%) (Figure 1B). Review/meta-analysis was the most common methodological approach (54.9% out of the 388 documents), followed by field experiment (19.0%) and observational field study (18.9%) (Figure C). The total number of authors was 1,280. The most prolific author was Montserrat Vilà (13 documents/3.4%), followed by Pilar Castro-Díez, Elías D Dana and Juan García de Lomas (7 documents each/1.8%), whereas 1,067 authors appeared in one single document (Figure 1D). Most documents were written in English (59.3%) and the remainder in Spanish.

Management (i.e. eradication and control) was the most frequent topic (31.8% out of 388 documents), followed by risk assessment (9.6%), survey/monitoring (9.3%), biology/ecology (7.6%), and impacts (7.4%) (Figure 2A). Studies focusing on populations and the autoecology of a single species were the most frequent (45.2%), followed by studies at the community/assemblage level (24.0%) (Figure 2B). The dominant

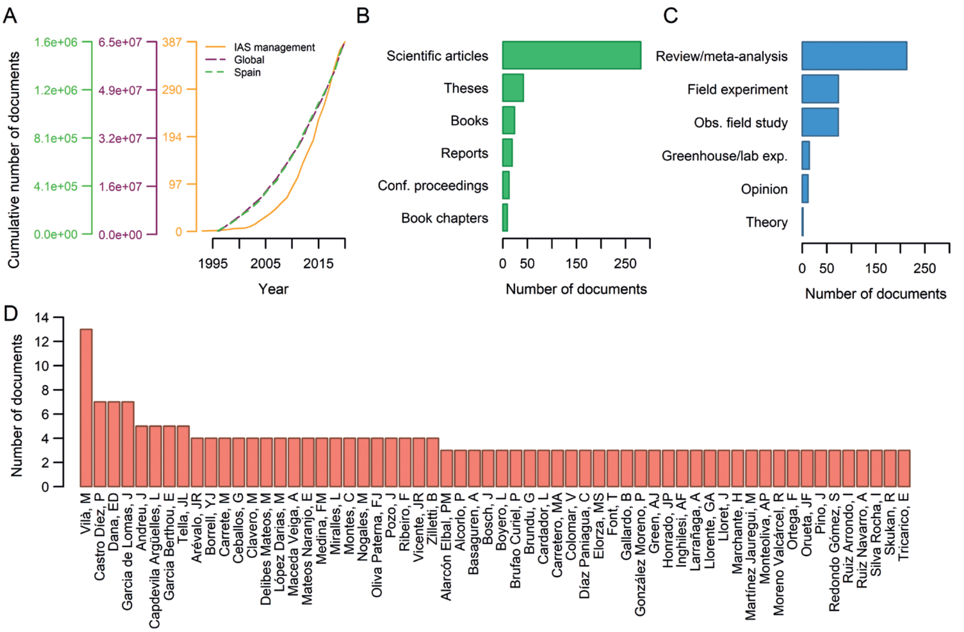

Figure 1. Cumulative number of documents on IAS management in Spain and cumulative number of scientific documents included in the Journal Citation Reports (JCRs), with no distinction by research area (**A**). Global series encompasses all the documents included in the JCRs, whereas the Spain series includes exclusively those produced in Spain (data retrieved from www.scimagojr.com/countryrank.php). Numbers of documents by types are represented in (**B**), methodological approaches in (**C**) and number of documents by the most prolific authors in (**D**).

management topic was generic/not applicable (48.0%) — i.e. documents that did not focus on prevention, eradication or control of IAS and did not involve direct manipulation of target IAS — followed by control (22.7%), whereas studies focusing on prevention and eradication were less frequent (17.5% and 11.7%, respectively) (Figure 2C). Studies on a local or national scale were more frequent (28.9% and 24.2%) than those on the intermediate (regional) or largest (supranational/global) scales (20.6% and 18.6%, respectively) (Figure 2D). The most frequent primary emphasis was basic (i.e. without direct manipulation of target taxa) (45.6%), followed by applied or interdisciplinary scopes (i.e. encompassing social and policy issues), both with similar prevalence (28% and 25.5%, respectively) (Figure 2E). The most frequent management treatments concerned impeding the establishment of further IAS through awareness-raising, regulation and survey monitoring (18.0%, 15.3% and 11.8%, respectively) (Figure 2F). Animal culling (9.1%) and plant mechanical and manual removal (11.5%) were the most common eradication and control treatments, whereas 8.2% of documents did not report specific treatments of target IAS (i.e. not applicable). The success of the proposed treatments as eradication or control methods was largely uncertain (not applicable/42.8% or unknown/23.4%) or partial (15%), which implies

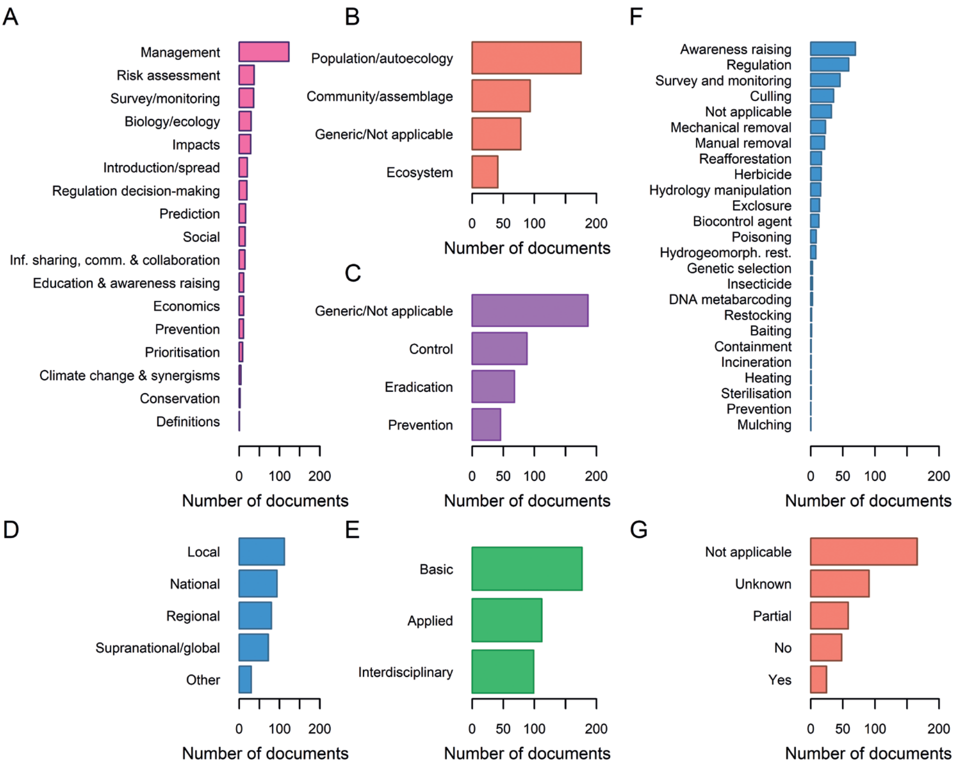

Figure 2. Numbers of documents by main topics are represented in (**A**), ecological organisation levels in (**B**), management topics in (**C**), spatial scales in (**D**), primary emphasis in (**E**), treatment in (**F**) and success in (**G**).

sustained management actions to control the target IAS (Figure 2G). About 13% of the studies focused exclusively on insular territories and 17% on protected areas.

The compiled studies involved 159 species or higher taxa (e.g. vascular plants). The largest number dealt with terrestrial ecosystems (50.4%), followed by inland waters (36.2%), whereas marine ecosystems and urban environments were the least common (8.3% and 5.0%, respectively) (Figure 3). Terrestrial vascular plants (10.4%) were the most frequent, especially eucalypts (*Eucalyptus* spp.) (1.6%), prickly pear species (*Opuntia* spp.) (1.3%), Hottentot figs (*Carpobrotus* spp.) (1.3%), Monterey pine (*Pinus radiata*) (1.3%) and cordgrasses (*Spartina* spp.) (1.0%). Amongst terrestrial animals, the most frequent species were the yellow-legged hornet (*Vespa velutina*) (1.6%), the pinewood nematode *Bursaphelenchus xylophilus* (1.3%), American mink *Neovison vison* (1.0%) and generic studies on vertebrates (3.3%), mainly birds (1.3%). In inland waters, generic studies were also the most common (7.5%), followed by those on fish management (7.0%). The most studied species in inland waters were the giant reed (*Arundo donax*) (3.1%) and the red swamp crayfish (*Procambarus* clarki) (1.8%), followed by generic studies on riparian vegetation (1.6%). Most studies on marine

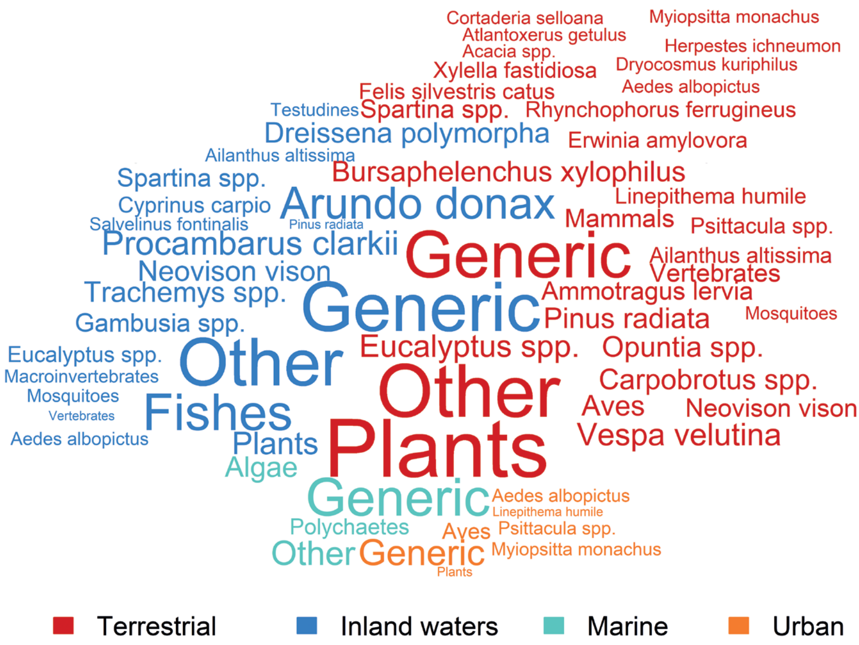

Figure 3. Word cloud depicting the proportion of documents per ecosystem type and taxon obtained using the function comparison.cloud of the R package wordcloud (Fellows 2018). The species or taxa occurring in less than two documents have been grouped within the category Other. Frequencies have been square root-transformed to facilitate reading the species.

environments were generic (4.4%) or focused on algae (1.8%) or polychaetes (1.3%). In urban environments, generic (2.1%) and bird studies (0.8%) prevailed, in addition to those on tiger mosquito (*Aedes albopictus*) (0.5%).

The association network displaying Cramér's V Index between pairs of features indicated great specificity regarding authors' preferences about publishing language and document type and on the management scales and treatment success of the conveyed experiences and approaches (Cramér's V > 0.91), but inferior regarding the target species (Cramér's V = 0.76). Subsequently, the association network highlighted the strong association between species and all other features (Cramér's V > 0.50), except with document type and protected area (Figure 4). The highest association of this group occurred between species and ecosystem type (Cramér's V = 0.66) and between species and insular territory (Cramér's V = 0.65). The connections between species, methodological approach and primary emphasis, as well as those amongst the latter two, were noteworthy. There was no strong association between the remaining features, except between the main topic and primary emphasis and the management topic (Cramér's V > 0.50). Insular territory and especially document type depicted the lowest association with the remaining features.

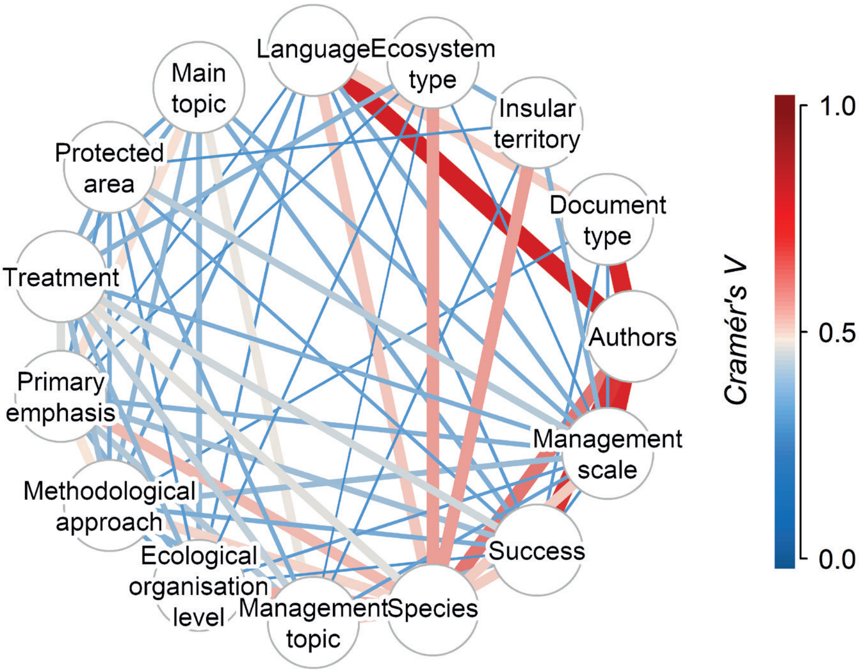

Figure 4. Association network displaying Cramér's V between features characterising the documents on IAS management in Spain. Connections are only depicted when the χ^2 statistic is significant ($P < 0.05$). Connection width and colour are based on Cramér's V and range from 0 (no association) to 1 (perfect association).

The most frequent studies were reviews and meta-analyses focusing on terrestrial ecosystems and providing general guidelines to manage invasive species at the national (6.5% out of the 388 documents), supranational/global (5.3%) and regional scales (4.3%) (Figure 5). They were followed by field experiments (manipulative) on terrestrial ecosystems addressed to locally eradicate specific taxa (3.3%). Reviews and meta-analyses on inland waters and those providing general guidelines to manage IAS at higher scales (i.e. regional to supranational/global) were also frequent (3.2% and 2.8%, respectively). Field experiments (manipulative) in inland waters addressed to eradicate (3.0%) or control (2.8%) specific taxa were in all cases local. The most frequent observational field studies on both terrestrial ecosystems (2.3%) and inland waters (2.0%) addressed generic aspects and were local. In contrast, documents focusing on marine ecosystems were scarce and studied generic aspects of marine invasion science with supranational/global (1.0%) or local (0.9%) perspectives. Manipulative field experiments to locally eradicate marine species were markedly rare (0.3%). Studies in urban environments were mostly reviews and meta-analyses addressing generic aspects at both supranational/global and local scales were the most abundant (0.5% and 0.5%, respectively). The proportion of field manipulative experiments to eradicate or control species was negligible.

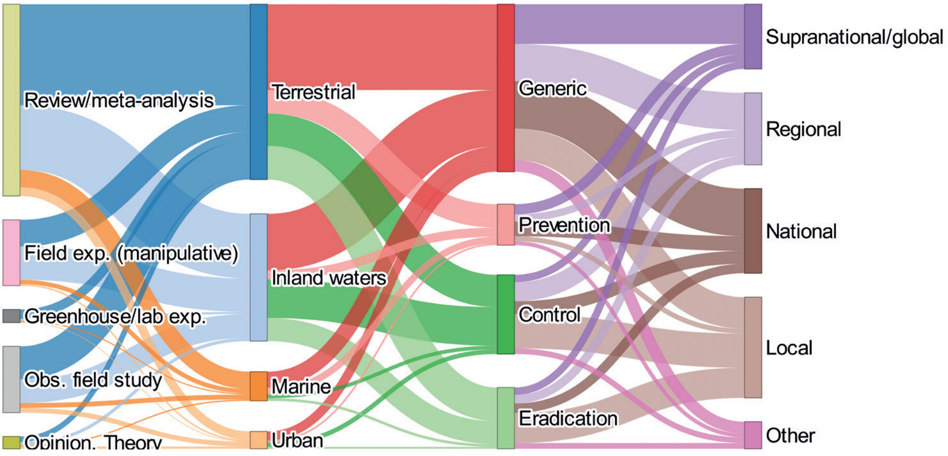

Figure 5. Alluvial diagram relating the methodological approach, ecosystem type, management topic and spatial scale of the compiled documents on invasive alien species (IAS) management in Spain. Connection width is proportional to the number of documents (An interactive version of this figure can be downloaded from https://doi.org/10.6084/m9.figshare.16547790.v1).

The most frequent approaches, described within terrestrial studies, focused on awareness-raising, survey/monitoring and regulation (7.3%, 6.8% and 3.1%, respectively out of the 388 documents). Most of them had no quantifiable (not applicable/17.2%) or unknown success (2.1%). This was followed by the use of biocontrol agents whose efficacy has not yet been tested (i.e. unknown, 1.6%) and unsuccessful culling of IAS (none and partial, 1.7%). The successful approaches most frequently reported combined herbicides and mechanical and manual plant removal (2.9% in total). In inland waters, awareness-raising and regulation were amongst the most frequently indicated approaches (3.9% and 3.0%, respectively), although with no quantifiable success (not applicable, 6.9%). Water level and flow regime manipulation was the most frequent management approach, but it was not tested (unknown, 2.3%) and occasionally turned out useless (0.7%). Culling and poisoning seldom worked (0.8% and 0.5%, respectively) and the success of most reported experiences was unknown or partial (1.6% and 0.9%, respectively). Hydrogeomorphological restoration, re-afforestation, plant removal and herbicide use were the most common approaches to control invasive riparian vegetation (1.2%, 1.1%, 1.6% and 0.7%, respectively). However, success of these treatments was partial or uncertain and only 0.6% reported successful experiences. The treatments for marine ecosystems followed a similar pattern and focused on preventative approaches: awareness-raising, survey/monitoring and regulation (1.9%, 1.0% and 0.9%, respectively), most of them with no quantifiable (not applicable/2.0%) or unknown success (1.6%). The only successful study involved raising awareness and DNA metabarcoding to confirm the elimination of the pygmy mussel (*Xenostrobus securis*) (Miralles et al. 2016). Awareness-raising, regulation and survey/monitoring were the most common approaches for urban environments (3.7% in total), but the few applied experiences indicated partial success through culling and plant removal and subsequent herbicide spraying (0.3%).

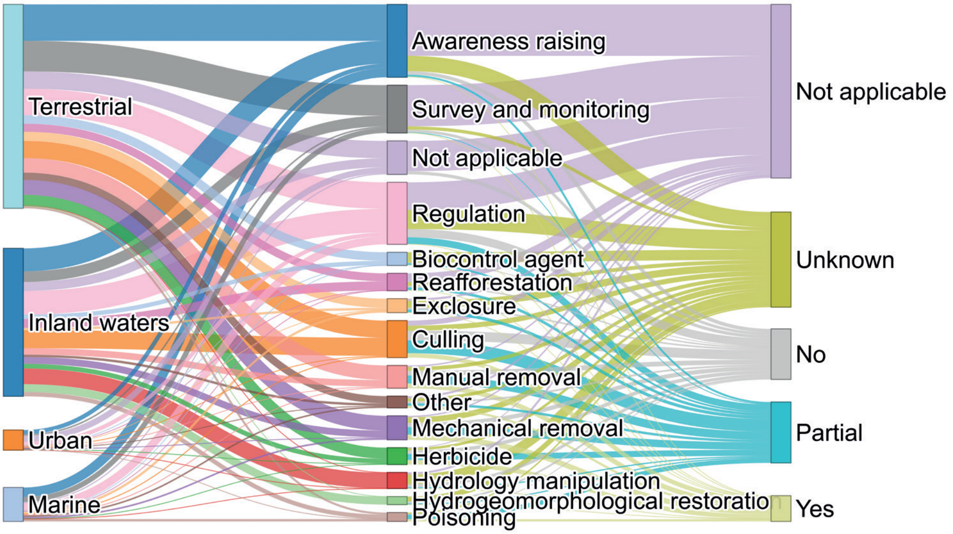

Figure 6. Alluvial diagram relating the ecosystem type, treatment and success of the compiled documents on invasive alien species (IAS) management in Spain. Connection width is proportional to the number of documents. The category Other includes mulching, prevention, sterilisation, heating, incineration, containment, baiting, restocking, DNA metabarcoding, insecticide and genetic selection (Alternative static and interactive versions of this figure relating species/taxa, treatment and success can be downloaded from https://doi.org/10.6084/m9.figshare.16547790.v1).

The collected keywords encompassed 1,145 different terms. The aggregation algorithm revealed 39 different research areas or clusters (Figure 7A), with 67 keywords occurring on ≥ 4 occasions (Figure 7B). The largest research area highlighted the importance of invasive plants amongst the Spanish literature on IAS management, the Mediterranean nature of much of the territory and the numerous studies carried out on this taxon in the Balearic Islands. The simplified network reflected the main topics of the study: invasive species and management, eradication and control. It also reflected research carried out on specific taxa, such as on the elimination of American mink (*Neovison vison*), which clustered with invasive species. Exclusion experiments on the European rabbit (*Oryctolagus cuniculus*) and feral cats (*Felis silvestris catus*) appeared in different research areas. The studies on feral cats were undertaken mainly in the Canary Islands as their research areas were connected. In addition, the resulting network highlighted the impacts on freshwater biodiversity caused by giant reed (*A. donax*) and aquaculture activities. The simplified network reflected the importance of the yellow-legged hornet (*V. velutina*) and mosquitoes (mainly the tiger mosquito *A. albopictus*) and the extensive use of species distribution models (SDMs), such as MaxEnt (Phillips et al. 2004), to foresee expansion trends and suitable regions. Specific topics (propagule pressure and ecosystem services) and introduction vectors (ballast waters, aquaculture and hunting) appeared in separate research areas. The simplified network reflected specific management approaches, such as general forest management, use of herbicides or emergence of citizen science. It also reflected studies addressing the interaction be-

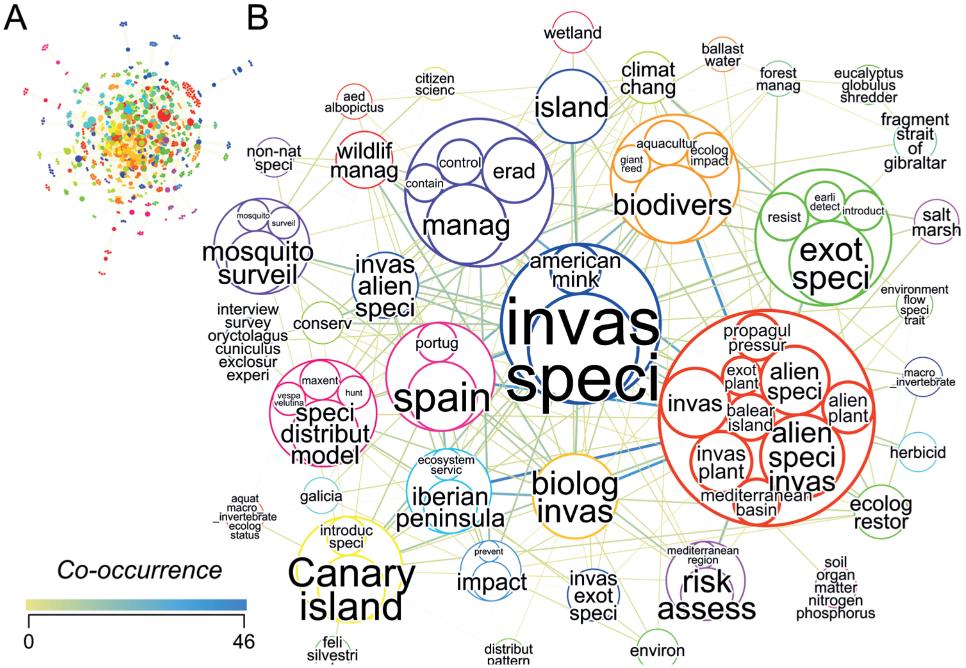

Figure 7. (**A**) Complete keyword co-occurrence network developed to visualise the importance of the research areas. Vertex colours are based on research areas or clusters and vertex size is proportional to the frequency of keyword occurrence. (**B**) Simplified network based on cluster centres and most frequent keywords (> Q_{95} or number of occurrences ≥ 4). Overall vertex sizes are proportional to the log-transformed number of occurrences and inner circles to the proportion within each research area. Label sizes have been rescaled to avoid overlapping.

tween invasions and climate change. In addition to the main toponymy used during the bibliography search, the network reflected specific regions and environments, such as the Strait of Gibraltar and Galicia (NW Spain) and the importance of wetlands and salt marshes. Moreover, the simplified network highlighted the importance of the archipelagos and islands within Spanish invasion science research, given that island and Canary Islands appear in differentiated research areas. It also revealed the multiplicity of terms used to name similar concepts, such as the terms alien species and exotic species that appear scattered throughout different research areas.

Discussion

Spanish literature on IAS management has been mainly theoretical (55% review/meta-analysis), with a balance between theoretical and applied studies similar to that reported in other studies on biological and ecological aspects of biological invasions (Andreu and Vilà 2007; Bayliss et al. 2013; Matzek et al. 2014, 2015). Nonetheless, IAS management literature has been under-represented compared to the Spanish and global trends on scientific production, although recently its share has grown. Altogether, this suggests that Spanish invasion science may also suffer from a knowing-doing gap caused by a preponderance of theoretical studies (Matzek et al. 2014, 2015). Moreover, scientific papers written in English constituted a large proportion of the compiled literature, which suggests that most of it may be too scientifically orientated to be directly applied (Andreu and Vilà 2007; Mungi et al. 2019; Copp et al. 2021). Nevertheless, scientific activity in Spain has also incorporated new forecasting technologies (e.g. SDMs/MaxEnt, de Medeiros et al. 2018) along with new approaches to engage society in IAS control (e.g. citizen science, Clusa et al. 2018) and for biomonitoring (e.g. DNA metabarcoding, Borrell et al. 2017). In addition, risk assessments and horizon scanning studies for decision-making formed a notable part of the literature, with direct implications for IAS regulation (Bayón and Vilà 2019). There was also discussion regarding the inefficiency of current codes of conduct and laws (Maceda-Veiga et al. 2013), aimed at enforcing policies to overcome the highlighted deficiencies.

The proportion of applied studies and field experiments was markedly low, which impeded rating the efficacy of most of the described approaches (66.2%). Moreover, studies on novel biocontrol agents, such as the use of pathogens (McColl and Sunarto 2020) were infrequent. In part, this is because these agents require rigorous risk assessment studies and are, hence, subject to strict regulations (Loomans 2021). Thus, species eradication and control experiences often relied on the use of herbicides, mechanical elimination or culling (e.g. Melero et al. 2010; Mateos-Naranjo et al. 2012) and successful approaches were restricted to small-scale areas, such as islets and ponds (e.g. Ferreras-Romero et al. 2016; Maceda-Veiga et al. 2017). Consequently, concerns of Spanish managers about the problem that too much research focuses generally on the ecological aspects of alien plants, rather than on specific cost-efficient management strategies (Andreu et al. 2009), can be considered, to some extent, applicable to most invasive alien taxa.

The proportion of documents per species and ecosystem type in Spain was similar to that estimated in other countries (Thomsen et al. 2014). Terrestrial species, mainly plants, attracted the bulk of the literature, followed by studies involving species of inland waters. By contrast, marine and urban environments were infrequent in the collected literature. The preponderance of terrestrial ecosystems and the associated species can be justified by the primary introduction pathways of terrestrial species (i.e. release and/or escape), which are largely related to forestry, livestock, agriculture and wildlife trade (Essl et al. 2015). Vascular plants are the most frequently introduced taxon worldwide; consequently, they were expected to receive the largest proportion of studies. However, the feasibility of managing terrestrial invaders or aliens, especially sessile species and stages of their life history (e.g. nests, Enríquez et al. 2013), is greater compared to aquatic species, due to the lower accessibility of these environments. Therefore, a publication bias towards successful studies with positive results on tractable terrestrial species is not discernible (Fanelli 2012; Booy et al. 2017).

Studies on terrestrial ecosystems involved all spatial scales (i.e. local, regional, national and supranational). However, applied experiments and experience were mostly local interventions, such as management of prickly pear species (*Opuntia* spp.) and the sentry plant (*Agave americana*) (Arévalo et al. 2015). By contrast, eradication and control of vagile terrestrial organisms proved to be economically unaffordable (e.g. American mink *N. vison*, Melero et al. 2010; Mañas et al. 2016), especially in a context of multilevel overlapping or competing public administrations with ill-defined jurisdictions and pervasive budget shortages (Tollington et al. 2017; Dana et al. 2019). In this regard, island territories were well covered by the collected literature, with several successful management experiences in these territories, such as the eradication of American mink (*N. vison*) in the Atlantic Islands National Park (Velando et al. 2017) or of the red palm weevil (*R. ferrugineus*) from the Canary Islands (Fajardo et al. 2019). Impacts of IAS on islands are likely to increase in the future, especially on oceanic islands, such as the Canaries and, to a lesser extent, on the continental Balearic Archipelago. Indeed, insular terrestrial ecosystems are generally the most threatened (Lenzner et al. 2020). Therefore, these two successful examples shed hope on the future management of IAS in Spanish insular territories.

The published research on terrestrial invertebrates and microorganisms appeared to be concentrated on a few species with direct impacts on economics and human health (e.g. yellow-legged hornet *V. velutina*, pinewood nematode *B. xylophilus* or tiger mosquito *A. albopictus*). However, further applied research and knowledge transfer is particularly needed to control invertebrates, due to the rising number of introductions worldwide (Saul et al. 2017; Seebens 2019). Such a task often requires strategies based on prevention and prompt eradication (e.g. ballast water sanitation) (Booy et al. 2017, 2020), but these were the least frequent of the categories amongst those implying direct manipulation of the target taxa. From a theoretical viewpoint, the compiled literature raises awareness and proposes changes to current regulations as its main approach, directed at preventing further introductions at a higher level of organisation. Legislation regarding IAS has become more restrictive over the years worldwide and Spain is also immersed in this useful trend (Turbelin et al. 2017; Maceda-Veiga et al. 2019). However, in light of the number of recent introductions (Muñoz-Mas and García-Berthou 2020), it can be concluded that the real effective capability of Spain to impede the establishment of further species is limited. This general pattern is shared with other European countries and is unlikely to change substantially in the near future (Seebens et al. 2021). Tackling the establishment of further terrestrial invertebrates and microorganisms will require further and stronger innovative and well-funded preventative approaches.

The number of studies conducted in inland waters was notably high due to the enormous number of established species and their associated economic costs (e.g. Durán et al. 2012; Muñoz-Mas and García-Berthou 2020). Some of this research was promoted by the Water Framework Directive (European Parliament & Council 2000), even if IAS are not explicitly mentioned therein (Boon et al. 2020). Our keyword co-occurrence network reflected the numerous studies recommending flow management as a way to control IAS (Sabater et al. 2008; Fornaroli et al. 2020). However, despite the schemes conducted in other countries (Kiernan et al. 2012), no applied examples in large and intermediate regulated river systems were found in the literature. River basin management plans increasingly account for the presence of IAS, but more emphasis on applied management of medium-to-large river systems is necessary (Boon et al. 2020). Nonetheless, applied studies of inland water ecosystems dealt with control of the giant reed *A. donax* (the most managed species appearing in the compiled literature) in relatively small areas (Bruno et al. 2019) or described experience in relatively small lentic environments (i.e. common carp *Cyprinus carpio* in ponds and lakes; Ferreras-Romero et al. 2016) and small streams (signal crayfish Pacifastacus leniusculus; Dana et al. 2010). Unfortunately, more research is needed to optimise water allocation schemes because climate change is facilitating the establishment of further IAS. Meanwhile, the increased demands of agriculture will reduce the availability of water resources to undertake the aforementioned actions (Rahel and Olden 2008; Escribano Francés et al. 2017).

In Spain, stowaway introductions in brackish and marine environments have also gained prominence (García-Gómez et al. 2020; Painting et al. 2020), causing a shift in the type of introduced species that can be framed within the current increase in global maritime traffic (Saul et al. 2017; Seebens 2019). In this regard, Spain enacted in 2004 the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention), which has been addressed in local studies (e.g. Moreno-Andrés et al. 2017), dissertations (e.g. Bartolomé Lamarca 2014) and is highlighted in the keyword co-occurrence network. However, new IAS records are being reported frequently. For example, the gastropod *Mitrella psilla* was recently found thriving on western coasts of Spain (Martínez-Ortí et al. 2020). The effectiveness of measures to fulfil the BWM Convention remains limited, which underscores the difficulties faced in managing marine IAS (Thomsen et al. 2014; Cuesta et al. 2016). Indeed, the number of first records whose most probable introduction pathways are ballast waters or biofouling (Davidson et al. 2018) and the increasing importance of aquaculture and related introductions (Nunes et al. 2015; Garlock et al. 2020) suggest these introduction pathways must be taken into account. It can, therefore, be concluded that marine invasion science should move towards our central focus in the future.

Worldwide, urban environments are becoming active introduction hubs (Gaertner et al. 2017). Indeed, there are several examples of initial IAS establishment in urban zones that have spread outwards over natural environments in Spain, such as *Lippia filiformis* (Casasayas i Fornell 1989) or the black-headed weaver *Ploceus melanocephalus* (Grundy et al. 2014). Ornamental plants and alien exotic birds kept as pets are perhaps the most striking and troublesome introductions in city surroundings (Riera et al. 2021), but other less-known taxa have been found on numerous occasions (e.g. *Pseudosuccinea columella* (Mollusca) Martínez-Ortí 2013). Besides the introduction of ornamental plants and tortoises and terrapins (*Trachemis* spp.), which have already spread over natural environments and prompted specific studies (Muñoz-Mas and García-Berthou 2020), the majority of Spanish management literature on urban environments has focused on birds (e.g. the monk parakeet *Myiopsitta monachus* and the rose-ringed parakeet *Psittacula krameri* (Álvarez-Pola and Muntaner 2009; Maceda-Veiga et al. 2019; Hernández-Brito et al. 2020; Saavedra and Medina 2020). Therefore, in the light of increasing urbanisation of the Spanish population and the relatively low number of specific studies, we conclude that prevention protocols and further studies, specifically addressed to urban environments, should be strengthened to encompass the full spectrum of potential introductions.

The compiled literature on IAS management in Spain does not particularly reflect budget reductions related to the Great Recession of 2008 (Catanzaro 2018). However, IAS management literature has been under-represented compared to overall scientific production trends and the current rise in publication rates has not compensated for this historical delay. Nonetheless, our compiled references only represent a small fraction of the total number of reviewed documents (388/3796 = 10.22%). Moreover, a significant number of documents were written in Spanish (n = 158; 40.7%). This finding deserves special attention as it handicaps knowledge transfer (Di Bitetti and Ferreras 2017) and biases conclusions inferred by international agents (Konno et al. 2020). However, it is not problematic from a national point of view because texts, documents and software packages assisting the process of decision-making by administrators and functionaries have proven to be most efficient when presented in local languages (Copp et al. 2021). Nevertheless, despite the proliferation of public repositories and open access publications, a wealth of information is still hidden away, not easily accessible to risk assessors, managers and researchers through standard search engines. For example, it is known that more than a hundred plant species have been managed by Spanish regional administrations (Andreu and Vilà 2007), but only the most frequent species generated accessible documents (e.g. reports). Altogether, it indicates that public agencies produce insufficient literature (sensu lato) as they focus on other tasks. Neither communication between managers and scientists beyond undertaking management action schemes nor protocols to evaluate their success are common practices in Spain. It would be beneficial for public agencies to encourage and facilitate such interguild contact, perhaps using legislative and labour changes, to disseminate applied experience in accessible ways.

Despite these recommendations and the highlighted deficiencies, Spanish literature on IAS management should not be considered completely defective. Recent studies on alien animal species, currently thriving in Spanish inland waters, indicate that no single management protocol can be applied to every taxonomic group, due to marked differences amongst species, introduction pathways and invaded habitats (Muñoz-Mas and García-Berthou 2020). Likewise, our study shows a strong association between species, taxon or group of taxa and the features/categories used to describe the compiled literature. This indicates that species-specific studies are often needed, which highlights how difficult and complex the task of IAS management is (Woodford et al. 2016; Portela et al. 2020; Yelenik et al. 2020). Our results should help to properly drive future research efforts towards IAS management in Spain. We recommend more research into applied techniques to shift the balance between theoretical and empirical studies, especially in inland waters and marine ecosystems due to their lower accessibility. The same need for more studies applies to urban environments, as they are often the bridgehead of IAS introductions. Renewed effort in prevention and prompt eradication should be made to fulfil, for example, the BWM Convention and impede further introductions into marine ecosystems. Finally, we encourage public agencies to support and strengthen the dissemination of applied experience and thus enhance know-how and knowledge transfer in the field.

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Supplementary material 1

Complete reference list and the features used to characterise the references

Authors: Rafael Muñoz-Mas, Martina Carrete, Pilar Castro-Díez, Miguel Delibes-Mateos, Josep A. Jaques, Marta López-Darias, Manuel Nogales, Joan Pino, Anna Traveset, Xavier Turon, Montserrat Vilà, Emili García-Berthou.

Data type: references and features

Link: https://doi.org/10.3897/neobiota.70.68202.suppl1

Supplementary material 2

Table S1. Table of features, categories and definitions used to characterise the compiled literature

Authors: Rafael Muñoz-Mas, Martina Carrete, Pilar Castro-Díez, Miguel Delibes-Mateos, Josep A. Jaques, Marta López-Darias, Manuel Nogales, Joan Pino, Anna Traveset, Xavier Turon, Montserrat Vilà, Emili García-Berthou

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