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20 years of marine bioinvasions research: Achievements and challenges for the Southwestern Atlantic

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Abstract. The study of marine bioinvasions was not homogenously developed worldwide and it is unclear the amount of research effort currently applied across the Southwestern Atlantic (SWA) countries. Through a comprehensive literature review, in this work, we analyze trends, gaps and achievements in the marine bioinvasion research efforts made along the coastal-marine ecosystems of the SWA and over the last 20 years of development, and we identify current challenges to further strengthening regional and international policies and management decisions concerning coastal-marine invasive species. Our analysis showed an exponential growth in the research effort, mostly focused on ecological patterns of non-native species, while other categories of studies (e.g., processes, management, methodological and socio-ecological) received significantly less attention. We found a high prevalence of national studies, while regional and international collaborations were virtually nil. Although the three countries in the region have made important achievements regarding the study and management of marine bioinvasions, changing this unbalance in the research effort between national and international collaborations, and specifically the limited scientific collaborations across the SWA countries, should be a top priority to better deal with marine bioinvasions in a regional and global context.

[Keywords: exotic species, invasive species, marine ecosystems, research effort, Brazil, Uruguay, Argentina]

Resumen. 20 años de investigaciones en bioinvasiones marinas: Logros y desafíos para el Atlántico Sudoccidental. El estudio de las bioinvasiones marinas no se desarrolló homogéneamente en el mundo y la cantidad de esfuerzo de investigación que se realiza a lo largo de los países del Atlántico Sudoccidental (ASO) no es clara. A través de una exhaustiva revisión de literatura, en este trabajo analizamos tendencias, brechas y logros en el esfuerzo de investigación en bioinvasiones marinas realizado en los ecosistemas marino-costeros del ASO a lo largo de 20 años de desarrollo, e identificamos los desafíos actuales para fortalecer las decisiones políticas y de manejo regional e internacional concerniente a las especies marino costeras invasoras. Nuestros análisis mostraron un crecimiento exponencial en el esfuerzo de investigación, mayormente focalizado en los patrones ecológicos de las especies no nativas, mientras que otras categorías de estudios (e.g., procesos, manejo, metodologías y socio-ecología) recibieron significativamente menos atención. Encontramos una alta prevalencia de estudios nacionales, mientras que las colaboraciones regionales e internacionales fueron virtualmente nulas. A pesar de que los tres países de la región realizaron importantes logros en relación con el estudio y el manejo de bioinvasiones marinas, cambiar este desbalance en el esfuerzo de investigación entre colaboraciones nacionales e internacionales —y específicamente en las limitadas colaboraciones entre países del ASO— debería estar entre las principales prioridades para afrontar las bioinvasiones marinas en un contexto regional y global.

[Palabras clave: especies exóticas, especies invasoras, ecosistemas marinos, esfuerzo de investigación, Brasil, Uruguay, Argentina]

Introduction

The study of marine and coastal biological invasions has grown notoriously over the past few decades. However, this growth was heterogeneous in time and space, being more evident in some disciplines and aspects of the problem than others and in some regions than others (Ricciardi et al. 2017). The entire field has been long dominated by ecological approaches which, for many years, focused on understanding relevant ecological patterns and processes (Lodge 1993). Many recommendations were recently made to optimize the way biological invasions are

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addressed in different regions of the world, considering local and regional needs and contexts (e.g., Hewitt and Campbell 2007; Ojaveer et al. 2014; Dehnen-Schmutz et al. 2018; Ricciardi et al. 2021). The Southwestern Atlantic (SWA), however, remains one of the least studied regions worldwide (Schwindt and Bortolus 2017).

The marine bioinvasion science is a young discipline in countries like Brazil, Argentina and Uruguay (Schwindt et al. 2018). Coordinated research efforts directed to understand the problem of biological invasions along the SWA started *circa* the year 2000 (Orensanz et al. 2002), generating a dramatic increase in scientific publications as well as in social awareness, which led to the first policies explicitly focused on invasive species (Masciadri et al. 2010; Creed et al. 2017a; Schwindt and Bortolus 2017). Nevertheless, it is yet unclear what perspectives and disciplinary approaches have been more developed than others over the last two decades, and it is also unclear if this development has led to tangible achievements within the region. In this work we analyze trends, gaps and achievements in the marine bioinvasion research efforts made along the coastal-marine ecosystems of the SWA over the last 20 years, and we identify current challenges to further strengthen regional and international policies and management decisions concerning coastal-marine invasive species.

Materials and Methods

The analyses were performed after a literature search, screening and categorization as detailed below.

Literature search

To search for applicable and reliable records (see Bortolus 2008, 2012), we conducted extensive searches in July 2021 using the multidisciplinary database of Scopus and complemented with Google Scholar as a supplementary source of evidence including the so called 'grey literature' (e.g., theses, technical reports, etc.) and resources in different languages (Haddaway et al. 2015; Schwindt and Bortolus 2017). The main goal of combining these searches was to capture all kinds of scientific research published in marine and estuarine ecosystems across the Southwestern Atlantic coast of Brazil, Uruguay and Argentina (Chile was not included due to its small proportion of territory along the Southwestern Atlantic and the lack of publications focused on it). We used the search terms 'alien', 'exotic', 'introduced', 'invasive', 'nonindigenous', 'non-indigenous', 'nonnative', 'non-native', and combined them with the environments 'marine' and 'estuarine' and these combinations were in turn combined with the countries in the target region, 'Argentina', 'Brasil', 'Brazil' and 'Uruguay' and with the oceanic denominations most commonly used in the literature, 'Southwestern Atlantic', 'south-western Atlantic', 'south-west Atlantic' and 'South Atlantic'. The Boolean operators 'AND' and 'OR' were used to combine synonyms about the status of the species, and the major topics. All keywords were used in English, Spanish and Portuguese. Our study spanned from 2000 to 2020, being 2000 recognized as the year in which research on marine bioinvasions started in South America (Orensanz et al. 2002; Schwindt and Bortolus 2017). All types of publications were considered except for those that matched one or more of the following exclusion criteria: 1) research focused exclusively on cryptogenic species, 2) studies on freshwater invasive species, 3) studies in aquaculture with non-native species not established in natural areas, and 4) studies not focused primarily on biological invasions or invasive species. Although some freshwater species may tolerate estuarine conditions, these species (e.g., *Corbicula fluminea*) were excluded to reinforce the focus on marine coastal ecosystems.

Literature screening

Once we finished gathering the literature from the previous step, we conducted specific screenings. First, all duplicates were eliminated. Second, all titles were checked for consistency with the topic studied. Third, all remaining abstracts were read to check for consistency with the exclusion criteria explained above. Fourth, the final list of documents was read in full to separate among the topics of our study (see below). To define the status of the species involved, we followed the recent categorization of non-native and cryptogenic species by Schwindt et al. (2020) for Argentina and Uruguay and by Teixeira and Creed (2020) for Brazil. These publications also offered us information about the establishment in natural areas of nonnative species used in aquaculture.

Literature categorization

To investigate the research effort, all publications were separated by five major areas: 1) patterns: includes mainly observational studies such as first records (when species are/is first detected in a country), reviews, range expansions (includes first reports in new areas within a country where the species already was/were recorded), taxonomy, distribution (i.e., faunistic and floristic studies), abundance, richness, diversity, life history, genetic, parasitism and trophic ecology; 2) processes: includes manipulative experimental studies directed to evaluate different ecological interactions (e.g., predation, facilitation), impact on life traits (e.g., recruitment, mortality) and ecosystem-level effects; 3) methodology: includes those studies mainly directed to evaluate tools and technologies (e.g., risk analysis, genetic tools) and scenarios and modeling (e.g., species distribution models, ecological niche modeling, etc.); 4) management: includes those studies directed to discuss or evaluate different management strategies (e.g., prevention, early detection, control, monitoring, eradication) and those directed to discuss legal and policy aspects, and 5) social-ecological: includes studies where society and humans are directly involved or affected (e.g., use/value of non-native species, economy, good quality of life [positively and negatively affected], perception, awareness, education, outreach, citizen science). In addition, to evaluate the degree of collaboration in the discipline (Schwindt and Bortolus 2017; Schwindt et al. 2020), all publications were categorized as national, regional or international depending on whether the study was developed entirely by researchers within one country (i.e., national), within two or the three countries in the region of interest (i.e., regional) or in collaboration with researchers from other countries worldwide (i.e., international). Also, to investigate trends in research effort, all publications were classified according to the year of publication. Thus, major categories and scientific collaborations were studied across time.

Literature analyses

First, we evaluated differences between research effort focused on 'patterns' with that focused on other areas. We compared the amount and rate (number of publications per year) of publications among the different research areas through a chi-squared test, and through generalized linear models (GLM), respectively. The latter were fit using year and research area as predictors and a Poisson error distribution using package 'stats' in R (R Core Team 2021). Multiple comparisons were performed whenever significant differences among research areas were detected. Following chi-squared tests, pairwise comparisons with Bonferroni correction were performed using the package 'RVAideMemoire' (Hervé 2021), while following GLMs, Tukey tests were performed using package 'multcomp' (Hothorn et al. 2021), both in R. To compare the amount of publications among the different topics within each major category, we used chi-squared tests and pairwise comparisons as previously explained.

Second, we used the visual representation provided by word clouds to explore the relative prominence of the terms most commonly used in the reviewed literature. For this exploration we selected the following four key sections: title, abstract, keywords and conclusions. These are the most important sections of a publication, being the title as the one where authors are expected to use the most attractive and descriptive terms to capture the attention of as many readers as possible. We used the keywords because they represent the main topics of the work performed and should not be repetitive with the words used in the title. Abstracts were considered because they provide a short and accurate description of what has been done and what are the key findings of the publication, complementing the title to attract potential readers. Finally, we considered the conclusions because they show how the key findings of the publication contribute to the advancement of the field, and often include a discussion in relation to future perspectives. In cases where the publication had not a separate conclusion, the last paragraph of the discussion was considered as a concluding remarks section. We built the word clouds using package 'wordcloud2' (Lang and Chien 2018) in R, after removal of all common words with no important intrinsic meaning such as 'can', 'will', 'also', thus', etc., as well as those used as keywords in our search (see a complete list in Supplementary Material 1). Additionally, only titles, abstracts, keywords and conclusions in English were considered; those in other languages were translated before the analyses.

Third, we studied the scientific collaboration network to examine patterns of national, regional and international collaboration among scientific institutions. From each publication, we extracted the affiliations of all the authors, each of these representing a node in the network. Then, we connected by a link two scientific institutions whenever they appeared as affiliations in the same study. The amount of studies in which two given institutions appeared as affiliations represents the link weight (a larger link weight indicates a greater collaboration among pairs of scientific institutions). To examine the degree of national, regional and international collaboration among the scientific institutions, they were classified according to their country of belonging for regional institutions (Brazil, Argentina or Uruguay) or 'other' for institutions in other countries. We used this categorization to compute network modularity (as defined in Clauset et al. 2004), which was then compared to 10000 similar networks with random groups through a permutation test (Reichardt and Bornholdt 2006). Network parameters were computed using the package 'igraph' (Csardi and Nepusz 2006) in R.

Fourth, we studied the language distribution of published marine bioinvasion research. We evaluated the relationship between the main language of each study, the availability of bi or trilingual versions of the abstract, and the type of publication through chi-squared tests of independence. All the analyses and figures were made with R version 4.1.1 (R Core Team 2021).

Results

We found 884 studies, 259 of which were identified as duplicates and therefore eliminated. The remaining 625 studies were first screened by title, and 85 of them were eliminated because they were unrelated to the topic we studied. After a thorough evaluation of the abstracts of the remaining 540 studies,

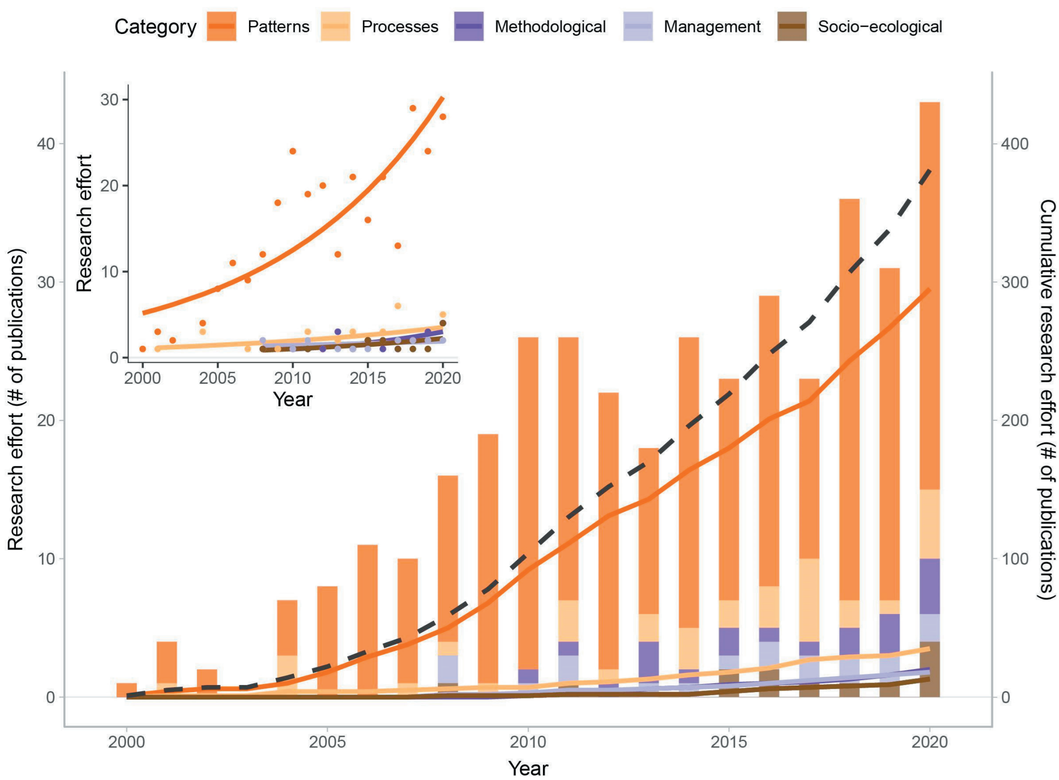

Figure 1. Research effort by category across the 2000-2020 period. Bars show the number of publications per year (left axis) and lines show the cumulative number of publications (right axis) by category (note that each of the 351 articles in this review may contribute to more than one category). Black dashed line represents the cumulative sum of publications for all categories. The upper-left insert shows the fitted generalized linear model (solid line) for the observed number of publications (dots) as a function of the year and the research area.

Figura 1. Esfuerzo de investigación por categoría a través del periodo 2000-2020. Las barras muestran el número de publicaciones por año (eje izquierdo) y las líneas muestran el número acumulado de publicaciones (eje derecho) por categoría (nótese que cada uno de los 351 artículos en esta revisión puede contribuir a más de una categoría). La línea negra cortada representa la suma acumulada de publicaciones de todas las categorías. El gráfico inserto en la esquina izquierda superior muestra el ajuste del modelo lineal generalizado (línea sólida) para el número observado de publicaciones (puntos) como función del año y del área de investigación.

189 of them were ruled out because they met our exclusion criteria. The last 351 studies were read in full and categorized following the five major areas detailed in Supplementary Material 2.

Over the 2000-2020 period, we found more studies focused on patterns than in any other type of research (χ^2=788.9, df=4, P=2.2x10^{-16}) (Figure 1). The research effort in marine bioinvasions showed an exponential growth with significant differences among the different research categories (R^2=0.88, χ^2=425.7, df=4, P=2.2x10^{-16}) (Figure 1). Studies focused on patterns not only started before but also at a significantly higher value than any other category. No significant differences were found in the annual growth rate (χ^2=1.55; df=4, P=0.818, mean=1.08±0.03) among categories.

Within the category of patterns, we found significant differences (χ^2=497.3, df=12, P=2.2x10^{-16}) among subcategories, dominated by studies describing the distribution of marine non-native species and followed by taxonomic studies, abundance, range expansion, life history, first records and richness (Figure 2). Except for research on processes, where studies focused on ecological interactions were more abundant than any other type of studies (χ^2=37.2, df=2, P=8.5x10^{-9}) (Figure 2), the remaining categories

Figure 2. Research effort, measured as the number of publications between 2000-2020, for each category (right labels) and subcategory (left labels), and discriminated according to the degree of scientific collaboration with which they were developed (see Materials and Methods). Different letters indicate significant differences between subcategories within each category based on a chi-squared test and *a posteriori* pairwise comparisons and an α=0.05. Each article in this review (n=351) could contribute to more than one category or subcategory.

Figura 2. Esfuerzo de investigación, medido como el número de publicaciones realizadas entre los años 2000-2020, para cada categoría (rótulos derechos) y subcategoría (rótulos izquierdos), discriminado de acuerdo al grado de colaboración científica con el cual se desarrollaron (ver Materiales y Métodos). Letras diferentes indican diferencias significativas entre subcategorías dentro de cada categoría basada en un test de chi-cuadrado y un test de comparaciones pareadas *a posteriori* y un α=0.05. Cada artículo en esta revisión (n=351) podría contribuir a mas de una categoría o subcategoría.

did not show differences between or among subcategories (methodological: χ^2=0.06, df=1, P=0.808; management: χ^2=0.20, df=3, P=0.978; socio-ecological: χ^2=0.84, df=7, P=0.558).

The most evident information provided by the word clouds is that the word 'species' played a superlative role in all sections of the literature reviewed, regardless of the nationality of the authors, the category in which the literature was or any other aspect considered in our search (Figure 3). Once we removed the word 'species', we unmasked a broader spectrum of words dominating the clouds in all sections. The Title and Abstract sections were mostly dominated by words related to descriptive research, like 'coral', 'Patagonia', 'first record', 'distribution', and 'reported'. The Keyword section was dominated by words associated with disciplines, like 'bioinvasion', 'invasion', or 'biological' (Figure 3), while the discussion/conclusion section showed a more integrative group of words covering various levels of ecological organization (species, population and community) and different approaches (ecological study, management, monitoring). In the later section the words 'study' and 'studies' stood out conspicuously and when all sections were considered, the genus 'Tubastraea' outstood as the only scientific name among the dominant words, despite being this genus present only in Brazil.

Regardless of the category, we found the research effort in all countries was predominantly national, while regional and international studies were virtually nil (Figure 4). The predominance of national studies was consistent across the time frame we studied (Figure 4). Not only national studies were dominant across time, but also collaborations among organizations and individuals from different regional countries across the SWA were low (Figure 5), and even international collaborations (i.e., outside the SWA), although diverse, were not consistent across time.

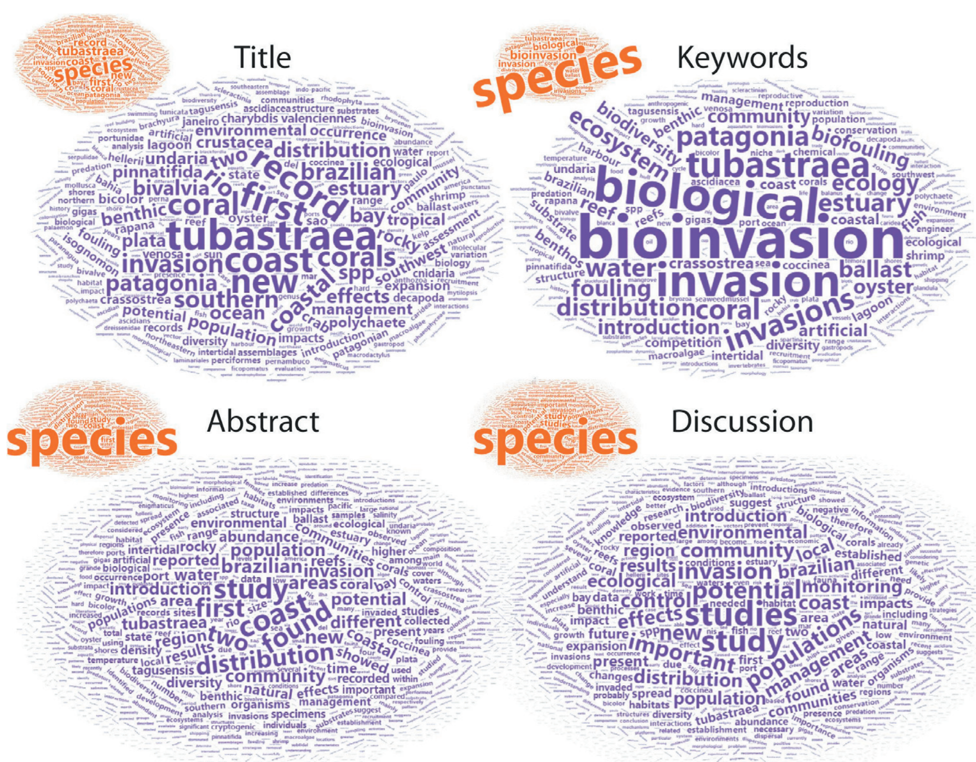

Figure 3. Wordclouds for the different key sections of the literature reviewed (title, keywords, abstract and discussion/conclusion), before (small orange cloud in the left top corner) and after (main cloud in purple) removing the word 'species'. Wordclouds were constructed using the English version of all the publications (using translations when original English versions were unavailable) and removing the words we used as searching criteria, as well as common words with no important meaning (see Supplementary Material 1).

Figura 3. Nube de palabras para las diferentes secciones claves de la literatura revisada (título, palabras claves, resumen y discusión/conclusión), antes (pequeña nube naranja en la esquina superior izquierda) y después (nube principal en violeta) de remover la palabra 'especie'. Las nubes de palabras fueron construidas usando la versión en Inglés de todas las publicaciones (usando las traducciones cuando las versiones originales en Inglés no estaban disponibles) y removiendo las palabras que usamos como criterios de búsqueda, así como las palabras comunes sin significado importante (ver Material Suplementario 1).

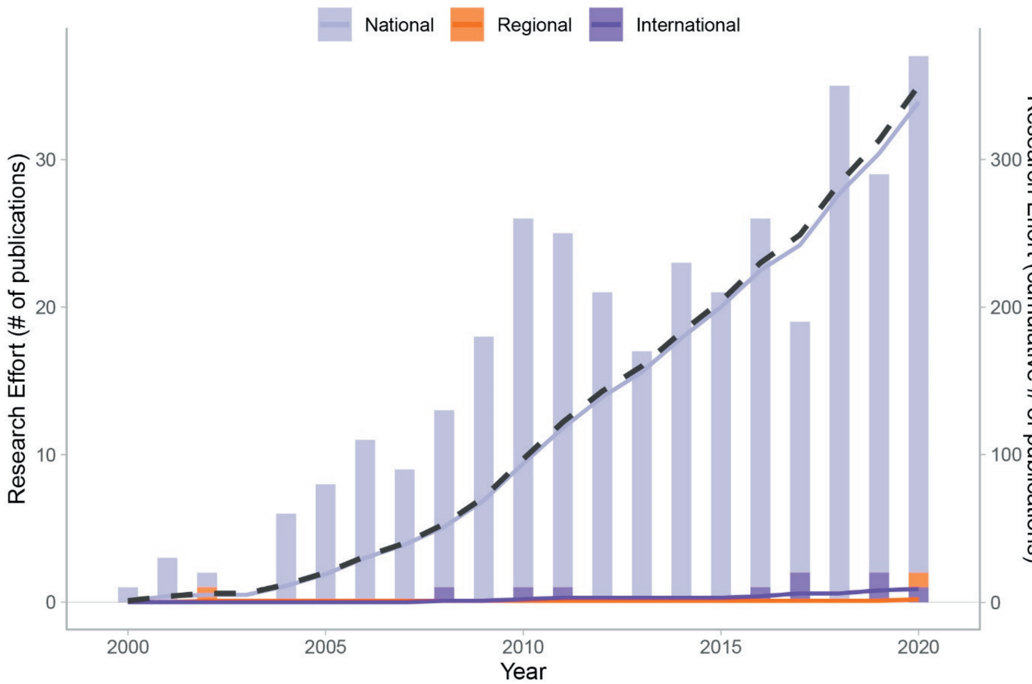

Figure 4. Research effort across time during the 2000-2020 period discriminated according to the degree of scientific collaboration. Bars show the number of publications per year (left axis) and lines show the cumulative number of publications (right axis) by category. Black dashed line represents the cumulative sum of all categories.

Figura 4. Esfuerzo de investigación a través del tiempo durante el periodo 2000-2020 discriminado acorde al grado de colaboración científica. Las barras muestran el número de publicaciones por año (eje izquierdo) y las líneas muestran el número acumulado de publicaciones (eje derecho) por categoría. La línea cortada negra representa la suma acumulada de todas las categorías.

Although intra-border interactions were abundant and often strong (Figure 5), we found a major gap in collaborations clearly separating Brazil (orange nodes) from the other two countries (violet and yellow nodes for Uruguay and Argentina, respectively). The three countries showed significantly stronger intra border collaborations than international ones (P<0.001 based on the permutation test on the modularity index), as well as abundant international collaborations with countries outside the studied region (gray nodes), however the latter were considerably less frequent than those within the region (i.e., the SWA).

Of all the studies surveyed, 91% (n=320) were published in English, 6% (n=20) in Portuguese and the remaining 3% (n=12) in Spanish. The language of the publications was associated with the country where the research was conducted (a country was assigned to a publication if all the affiliations belonged to one country, else, in the case of regional and international publications, the country was labeled 'other') (χ^2=30.3, df=6, P=3.4x10^{-5}), with more publications than expected written in Spanish by authors from Argentina and Uruguay, and more in Portuguese by those from Brazil. No influence of country of origin was detected in the use of English in the publications (χ^2=0.44, df=2, P=0.802), with nearly 90% of the publications from each country being in English.

Of all the studies with abstracts, 16% (n=52) provided bi- or trilingual versions. This percentage was highly dependent of the language of the study (χ^2=70.3, df=2, P=5.4x10^{-16}), with more Spanish and Portuguese publications supplying bi- or trilingual abstracts than publications in English, which commonly lacked abstracts in other languages. The language used in the studies was also dependent on the type of publication (χ^2=80.4, df=2, P=2.2x10^{-16}), with journal articles being mostly published in English, while most Spanish and/or Portuguese publications being represented by books, chapters, reports and theses.

Discussion

Trends and gaps

Biological invasions in marine environments remain less studied than in terrestrial

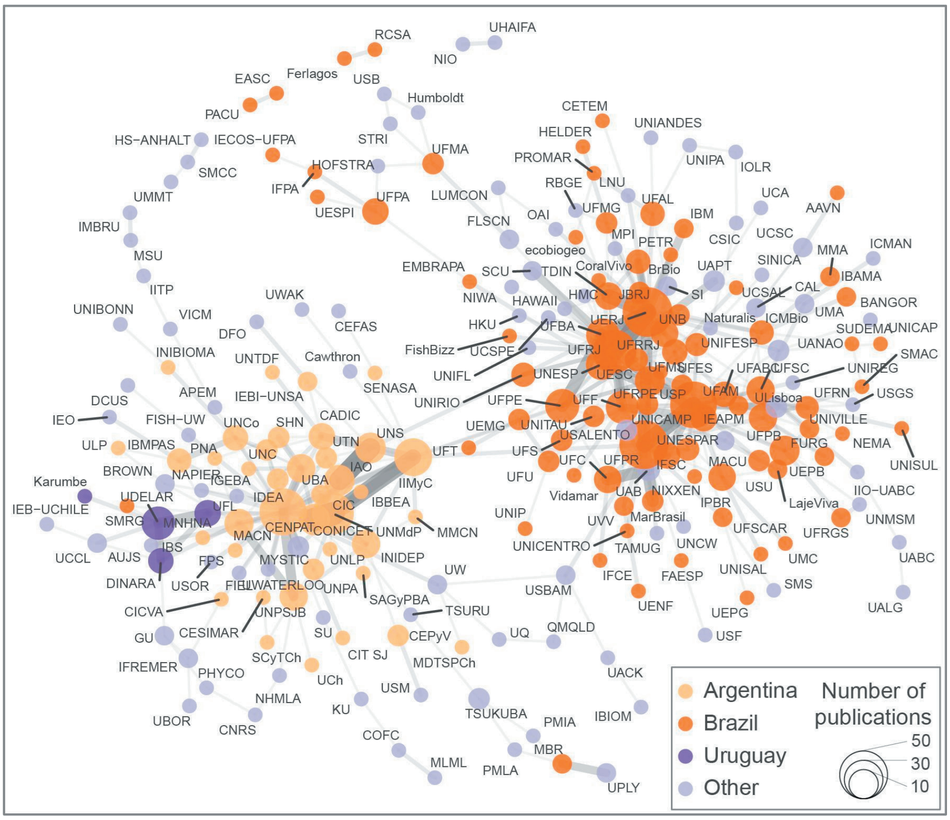

Figure 5. Network showing the scientific collaboration for marine bioinvasion research in the SWA. Nodes represent the institutions mentioned as affiliations in the publications (see Supplementary Material 3 for the list of abbreviations) and links connect institutions that appear in the same publication. Node size is proportional to the number of publications where it appears as an affiliation, and link width is proportional to the frequency with which both institutions appear in the same publication. Node position was determined based on the Fruchterman-Reingold algorithm.

Figura 5. Red de colaboraciones científicas para investigaciones en bioinvasiones marinas en el ASO. Los nodos representan las instituciones mencionadas como afiliaciones en las publicaciones (ver Material Suplementario 3 para la lista de abreviaturas) y los enlaces conectan las instituciones que aparecen como afiliaciones en una misma publicación. El tamaño de los nodos es proporcional al número de publicaciones en las que figura como una afiliación, y el ancho del enlace es proporcional a la frecuencia con la que ambas instituciones aparecen en una misma publicación. La posición de los nodos fue determinada en base al algoritmo de Fruchterman-Reingold.

environments, and this bias might be even greater in those regions where logistics and financial support are less available (Pyšek et al. 2008, 2020). Our analyses reflect how this problem was addressed over the last 20 years along the SWA coast, where research effort in marine bioinvasions increased significantly (4200%!) over this period. The exponential trend suggested by previous estimates (Pyšek et al. 2008; Schwindt and Bortolus 2017), is radically changing the status of the SWA, previously considered one of the largest regions with fewest studies on bioinvasions (Schwindt et al. 2020). This outstanding regional performance is mostly sustained by the publication of baseline studies on ecological patterns, especially on the presence and distribution changes of non-native species, while less research effort was directed to understand the impacts of these species, the community and ecosystem processes they participate in, or the methods and management strategies applied to control them. There is no doubt that if the description of the abundance and distribution patterns is incorrect, the knowledge and the interpretation of the ecological processes will also be incorrect (Underwood et al. 2000). However, understanding ecological processes is essential to support sound management decisions, while descriptive associations and correlations are known to be insufficient and can even be misleading. Taxonomy-based studies are of critical importance to correctly identify species and to establish their status as native or non-native and to design further management strategies (Bortolus et al. 2008). Nevertheless, it is highly concerning that other studies, such as those directed to evaluate the impacts of invasive species or methods for prevention and management strategies, did not receive enough attention. Another important gap is the virtual lack of effort directed to address the human dimensions of biological invasions in the region and the lack of interdisciplinary approaches involving the social sciences (Bortolus and Schmindt 2022). Different hypotheses might explain these results, in particular the scarcity of experimental studies. For instance, marine ecosystems are complex to understand and to work on, because they require special human capacities and equipment (e.g., SCUBA diving, boat operators, etc.), logistics and funding. In addition, ecological experiments focusing on species interactions are difficult to perform over long periods of time, due to harsh environmental conditions intrinsic to aquatic systems. Finally, the socioeconomic reality of these countries determines an agenda mainly focused on finding solutions to economic problems rather than environmental ones, and research in biological invasions and marine ecosystems is usually not among the highest priorities (United Nations 2018).

The fact that 'species' was by far the most important word across all word clouds and analyses suggests that, for the literature studied, a strong prevalence of faunistic, floristic, taxonomic and autoecological approaches centered more in species than in populations, communities, ecosystems or landscapes. This is reasonable considering that the discipline of Biological Invasions is relatively new in the region and that any sound study aiming to understand the operating ecological processes needs strong descriptive baseline information. Once the word 'species' was removed from the analysis, words denoting a rich variety of frameworks and perspectives were unveiled, including the management, monitoring and control of marine invasive species. However, the scarce research effort we found directed to understand and contribute to these other issues over the last 20 years (Figures 1 and 2) shows a critical lack of balance that inevitably conditions the way in which this region will deal with marine bioinvasions in the near future. This unbalance is aggravated by the sustained exponential increase we found in the publication of patterns rather than processes. Correcting this unbalance between different perspectives and frameworks should therefore be among the top priorities for the three countries, in order to optimize the efficiency of their collaborations to deal with marine biological invasions.

Our results show a lack of well-coordinated and long-lasting international collaborations among the countries within the region as well as worldwide. This is a major gap, and it was highlighted in previous reviews for this region (Schwindt and Bortolus 2017; Measey et al. 2019; Schwindt et al. 2020) and also worldwide (Earley et al. 2016; Hulme 2021). Over the twenty years that we surveyed, the three countries involved have built and strengthened national interactions that promoted the growth of invasion science as a discipline. However, international collaborations seem to remain relatively scarce and sporadic. In this context, Brazil appeared as the most isolated country in the region, even though it produced the largest amount of literature in the field. On the other hand, although Uruguay and Argentina strengthened their mutual collaborations with key publications for the discipline (Orensanz et al. 2002; Schwindt et al. 2018; Schwindt et al. 2020), we found that most of these interactions are weak and ephemeral, compared to those within these countries. However, since invasive species move from one place to another regardless of political frontiers, it is essential to achieve good communication flow by coordinating local, regional and international efforts to maximize success in dealing with biological invasions. There are at least ten non-native species distributed throughout the SWA, 24 other species are shared by at least two of the countries in the region (Schwindt et al. 2020; Teixeira and Creed 2020) and several others have been predicted to expand their distribution over the entire region, under present conditions or future scenarios of global change (e.g., Dellatorre et al. 2014; Lins et al. 2018; Zhang et al. 2020). Scientific collaborations are essential to promote and speed up further agreements among states (Measey et al. 2019). They provide the basic initial understanding about biological invasions, for example, by analyzing vectors and pathway patterns to design and implement risk assessment plans. Scientific collaborations can foster global solutions and need to be facilitated and supported by institutions and governments (e.g., Munawar et al. 2017; Fowler et al. 2020). Regional and international cooperation and support is essential to increase local capacities, for example, by providing the necessary multinational legal frameworks and special funding to build networks devoted to solving these problems (Ricciardi et al. 2021).

Achievements

Brazil, Uruguay and Argentina achieved many goals in the study of marine invasive species, as well as in the prevention and management, policy making and implementation of strategies, awareness, outreach, educational programs and inserting this global problem in the local agendas. In most national and regional congresses, specific symposiums and workshops were devoted to the discussion of marine bioinvasions. Moreover, the two main international meetings focused on marine bioinvasions (Marine and Freshwater Invasive Species, and the International Conference on Marine Bioinvasions) were recently celebrated for the first time in South America (Munawar et al. 2017; Fowler et al. 2020), where researchers from the three countries engaged in fruitful discussions. In the policy sector, at the regional scale the three countries signed in 2019 an agreement to work together in the guidelines for a prevention, monitoring, control and mitigation plan for invasive exotic species (MERCOSUR/GMC/RES. Nº 38/19). This agreement is the first step towards regional cooperation, but specific details are urgently needed, for example, specific roles of each government, stakeholders to be involved, a working agenda with specific targets and priorities, etc. Agreements are an important milestone but need to be pragmatic and foster for quick and specific actions. Little progress was made towards the Aichi Biodiversity Target related to invasive species at the global scale (Díaz et al. 2019), however at national scales in the SWA there have been some significant advances. These were highly variable among countries and developed almost independently from the neighboring countries, as detailed below.

Brazil. The first review of marine non-native invasive species in Brazil was published in 2009 (Lopes et al. 2009). This review took a very conservative approach and included only 58 species with well-supported evidence of introduction (Rocha et al. 2013). After the rise in the interest in invasive species, the updated number of non-native marine species reached 138, showing an increase of 160% in ten years (Teixeira and Creed 2020).

An important milestone for research on invasive species in Brazil was the Global Ballast Water Management Program (GloBallast) initiated by the International Maritime Organization (IMO) to regulate the control and management of ballast water in six developing countries worldwide between 2000 and 2004 (Leal Neto and Jablonski 2004). This program was planned to develop activities to prepare the country for the implementation of the International Convention for the Control and Management of Ships Ballast Water and Sediments. The Port of Sepetiba (now the Port of Itaguaí) was chosen as a pilot area for conducting biota surveys, risk assessments, environmental education programs and ballast water sampling. The risk assessment study highlighted the importance of domestic navigation as a potential means of dispersion and secondary introduction (Clarke et al. 2004). The Ministry of the Environment was the lead agency for the execution of this program, which had the collaboration of several universities and research institutions in the country. Awareness and environmental education campaigns were conducted as part of a Communication Plan, through a poster competition, distribution of posters and videos and maintenance of a website. Some countries in South America were also involved with the aim of establishing regional cooperation, and within this context, Argentina developed a baseline report (Schwindt et al. 2010).

Another important milestone was the creation of a legal instrument, the NORMAM-20 (Castro et al. 2018), by the Brazilian Maritime Authority in 2005, to coordinate the control and management of ballast water in Brazilian ports. The Brazilian Government, pressured by the invasion of the invasive golden mussel *Limnoperna fortunei* in national and international, maritime and river waters, which caused serious fouling problems in industrial facilities (Calazans et al. 2013), was one of the first IMO State Parties to ratify the International Convention for the Control and Management of Ships Ballast Water and Sediments in 2005. The Ballast Water Convention entered into force in September 2017.

Despite the increasing concern and the regulations created to study, manage, and/or control the potential impacts of ballast water in Brazil, several non-native species were found thriving in fouling communities on the hulls of ships and oil platforms (Paula and Creed 2004; Ferreira et al. 2006; Junqueira et al. 2009; Creed et al. 2017a), including the invasive scleractinian corals, *T. coccinea* and *T. tagusensis*

(Miranda et al. 2016; Soares et al. 2016; Creed et al. 2017b). Currently considered the most troublesome invasive marine species along the Brazilian coast (Schwindt and Bortolus 2017), these corals led the Brazilian government to develop a plan focused on the 'Prevention, Control and Monitoring of the Sun Coral (*Tubastraea* spp.) (https://bit.ly/3CEkHZH). Other initiatives to contain the spread of the sun coral at the country level include the Sun-Coral Project launched in 2006 (Creed et al. 2017b). Control by physical removal, and subsequent monitoring, has been conducted at some sites along the Brazilian coast, but its success in the long term depends on repeated removals and on intensive efforts covering extensive areas (Creed et al. 2021). Management by physical removal is also important particularly in the Marine Protected Areas (MPA). The history of control actions in the Marine Protected Area Reserva Biológica Marinha do Arvoredo (REBIO) in Santa Catarina state between 2012 and 2019 shows the relevance of these actions in trying to contain the invasion (Crivellaro et al. 2020) as well as in the Tamoios MPA in Rio de Janeiro state (Gomes et al. 2015).

More recently, Brazil was elected Leader Partnering Country (LPC) for the new GloFouling project launched in 2019. One of the first goals of this project is to implement the IMO Biofouling Guidelines for Shipping and Offshore Industries launched in 2011 and encourage their revision by each LPC. Similar to GloBallast, the other goals are capacity building, awareness raising and technical assistance. In 2018, Brazil approved a new text for the National Strategy on Invasive Alien Species and set up an implementation plan with a 6-year horizon (2018-2024) in which actions, articulations, costs and deadlines are expected to be defined. Currently, the implementation of the National Strategy has resources from the Pro-Species Project: National Strategy for the Conservation of Endangered Species financed by the GEF (Global Environment Facility Trust Fund). One of the subprojects launched in 2020 focuses on the prevention and early detection of invasive alien species and rapid response, including the development of a general protocol and three specific manuals (marine, freshwater and terrestrial), as well as a proposal for the structure and functioning of a network of collaborators.

Inspired in the IPBES (Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services), Brazil started in 2021 the Brazilian Diagnosis on Invasive Alien Species, Biodiversity and Ecosystem Services for the Brazilian Platform on Biodiversity and Ecosystem Services (BPBES). It seeks to place the issues of conservation and sustainable use of biodiversity and ecosystem services at the heart of the country's development model.

Uruguay. The National Strategy for the Conservation and Sustainable Use of the Biological Diversity (2016-2020) included 1) the creation of a list of invasive exotic species of Uruguay; 2) a national expert committee on invasive exotic species (CEEI), and 3) a database of exotic and invasive species (InBUy) (inbuy.fcien.edu.uy). Although this database is still in progress, it includes several marine species (Masciadri et al. 2010). In 2018, the CEEI established a protocol for rapid response against invasive exotic species, priorities for their management and other documents related to their impacts, being the bivalves *Limnoperna fortunei* and *Corbicula fluminea*, the most troublesome invasive species in aquatic ecosystems (https://bit.ly/3GBEwmL).

Although Uruguay has not approved the Ballast Water Management Convention (BWMC), the maritime authority released the guidelines for the management and control of ballast water for ships in 2006 (DM 109) with similar objectives to those agreed in the BWMC. In 2010, aiming to reduce the spread of the non-native rapa whelk *Rapana venosa* and to improve the invasive species database, an awareness campaign was promoted among local communities offering to pay for each individual captured (https://bit.ly/3pMIClP). Once established, eradication and control of marine invasive species is practically unfeasible and sometimes there are no options other than to adapt (Howard 2019). In this sense, the rapa whelk, which was introduced initially in Argentina and Uruguay but recently discovered in Brazil (Spotorno-Oliveira et al. 2020), was included in a socioeconomic study (Carranza et al. 2012). This is a long way process, but early results show that this species has the potential to be commercialized in artisanal fisheries and sold in local restaurants.

Argentina. Argentina launched the National Strategy on Invasive Exotic Species (NSIES) project in 2016 and it was approved in 2022, showing several advances. In 2021, the Ministry of Environment and Sustainable Development approved the risk analysis protocols for invasive exotic species and the national list of invasive, potentially invasive and cryptogenic species where over 60 marine species were included (RESOL-2021-109-APN-MAD, https://tinyurl.com/c9wavb2j). Also, as part of this work, the national invasive species database was officially launched with more than 100 marine species reported. From an educational perspective, the NSIES project published and distributed a book with activities for primary schools (https://bit.ly/3GsXdsN) and awareness materials, being the most important a series of documentaries available on the internet (https://bit.ly/38dO5Ix). All these advances are highly important but not enough to prevent and manage invasive species, especially in marine ecosystems. The NSIES needs to be implemented in the short term if Argentina aims to meet the next goals by 2030 proposed by the IUCN Invasive Species Specialist Group (ISSG) (https://bit.ly/3bndAZk). These goals propose to abate the impacts of invasive species upon native biodiversity and to reduce the rate of introductions, preventing further impacts.

In 2014, Argentina approved the Ballast Water Management Convention (Law 27011) and in 2017 the maritime authority (Prefectura Naval Argentina) published all the regulations regarding this law for its implementation (DPAM N° 07/2017; Abelando et al. 2020; Abelando 2021). Concerning the management of biofouling, the country does not have specific legislation and regulations but there were two important advances in this matter. The first one is the prohibition of in-water cleaning procedures for hull vessels in Nuevo Gulf, a designated MAB-UNESCO protected area in Patagonia, which was historically used for this practice due to the clean and calm waters. The second one is the publication of the best practices guide for small vessels and nautical equipment (https://bit.ly/3xltdtw). Although they are not mandatory, this guide provides all the information, procedures and guidelines to reduce the spread of marine invasive species. It also includes a short guide and the contact information in case a new non-native species is early detected. Under the umbrella of the NSIES, an early detection and rapid response plan for marine invasive exotic species in port areas was agreed among stakeholders after several workshops. However, the approval is still pending since 2018, which delays effective solutions.

While policymakers are still discussing and negotiating decisions, management solutions are accumulating based on scientific evidence. Hull biofouling management, although a priority to prevent new species introductions, is highly difficult and a real impediment for large vessels when dry docks are not widely available, as occurs in Argentina, or unless specific technologies are developed. However, for small recreational and fishing vessels the haul out and cleaning option is more accessible. Castro et al. (2020) designed and put into practice a 'cleaning-by-beaching' method for small vessels in shorelines with macrotidal regimes. This procedure offers the additional opportunity to monitor marine bioinvasions and to detect new non-native species. Surveillance and long-term monitoring are essential strategies for early detection of marine invasive species. In this sense, Castro et al. (2021) provided robust evidence about the importance of implementing programs directed towards the early detection and rapid response. During the monitoring of the newly introduced Pacific oyster *Crassostrea (=Magallana) gigas* on shipwrecks, two solitary ascidian species (*Styela clava* and *S. plicata*) were early detected and removed. Scientists advanced in the study of these species from many perspectives and provided essential information for policymakers, such as taxonomy, modeling and vector and pathway analysis (see also Battini et al. 2019). Scientific evidence is highly valuable and needs to be taken into consideration in management decisions.

Challenges

For the nations in our target region, in our view the first top priority is the urgent need to effectively coordinate long term international cooperation, not only within the region but also worldwide. Governments must create the necessary legal, logistic, and financial conditions that will secure the international cooperation needed to cope with the problem of marine biological invasions. Due to the intrinsic nature of this problem, where the actions in one nation will affect the others, without solid long-lasting international coordination progress is not viable (Stoett 2010).

A second top priority challenge is to increase the research efforts directed to understand the processes and mechanisms that create and shape the patterns already described. The strong positive trend we found in the growth of research efforts historically focused on patterns rather than processes suggests that achieving a balance between these two categories will take time. Therefore, satisfying the urgent need for regional/global well-coordinated managing strategies will require the use of pragmatic social-based perspectives to redirect future research efforts in an optimal way, as well as the setting of official agendas that include specific goals, responsibilities and deadlines to meet. Finding a balance between these categories should not result in a detrimental withdrawal of support directed to understanding patterns, as these studies are the essential baseline of any sound environmental knowledge and support museum collections. In this vein, again, considering the need for strengthening the coordination of regional work, multinational training courses and workshops must be developed (Abelando 2021). A first step in this direction is to implement coordinated long-term monitoring programs, not only directed to produce baseline studies, but also to track the effects of non-native species within recipient ecosystems. Having long term series of ecological and environmental data allow us to anticipate future scenarios and take science-based management decisions (Lehtiniemi et al. 2015).

Finally, we advise all governments involved supply not only the legal framework, but also, facilitate the creation of a network with specific responsibilities for each member (for instance, bestowing the enforcement power to a specific force, defining representatives for each team in the network, etc.), and establishing the rules for this network to interact efficiently across international borders. There are many tools and technologies developed for preventing and managing invasive species worldwide, and it is urgently recommended to implement them according to the specific needs across the region. Going in this direction will surely maximize effectiveness while lowering costs in the long term.

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