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Management in Practice

Marine bioinvasions in Chile: A national research and conservation management agenda

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Abstract

Non-indigenous species have been widely recognized as major drivers of biodiversity loss. However, management in marine ecosystems entails particular challenges of detection and control, with an approach which requires stakeholders from the government, academia and the public. To generate a first approach to what should be the national Chilean agenda for non-indigenous species (NIS) management, a workshop was convened at the Universidad Católica del Norte in Coquimbo on the past, present and future of marine bioinvasions in Chile. The workshop, with more than 60 participants, including academics and public services, gathered information from the published literature on the state of the art of marine bioinvasions in Chile and proposed a work agenda for the coming years. The results highlight that the design and implementation of more focused and effective management policies and programs will be required to potentially reduce the rates of new invasions and identify mitigation strategies. We present the first proposed NIS research and management agenda for Chile developed through a collaborative process between researchers and the Chilean government, with a joint vision of both the challenges and solutions.

Resumen

Las especies no nativas han sido ampliamente reconocidas como grandes impulsores de la pérdida de biodiversidad. Sin embargo, la gestión en ecosistemas marinos conlleva desafíos particulares de detección y control, y cuyo abordaje requiere de actores del gobierno, la academia y la sociedad civil. Para generar un primer acercamiento a lo que debería ser la agenda nacional para especies no autóctonas (NIS) se convocó un workshop en de pendencias de la Universidad Catolica del Norte en la ciudad de Coquimbo que abordó el pasado, presente y futuro de las bioinvasiones marinas en Chile. El taller, con más de 60 participantes, entre académicos y servicios públicos, levantó información de la literatura publicada sobre el estado de arte de las bioinvasiones marinas en Chile, y una propuesta de agenda de trabajo para los próximos años. Los resultados destacan que se requerirán el diseño e implementación de políticas y programas de gestión más enfocados y efectivos para reducir potencialmente las tasas de nuevas invasiones e identificar estrategias de mitigación. Presentamos la primera propuesta de agenda de investigación y gestión de NIS para Chile desarrollada a través de un proceso llevado de manera colaborativa y coordinada entre la academia y el estado Chile trabajan con una visión común tanto de los desafíos como de las soluciones

Key words: nonindigenous species, exotic species, invasion vectors, ballast water, biofouling, invasion ecology

Introduction

The introduction of non-indigenous species (NIS) is now widely recognized, along with habitat destruction, over-fishing, reduced water quality, and climate change, as one of the great drivers of change impacting the economic security, ecosystem services, and biodiversity of the world's oceans (Nellemann et al. 2008; Rahel et al. 2008; Kennish 2015). The Global Assessment Report on Biodiversity and Ecosystem Services developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services has further described bioinvasions as one of the main direct drivers for biodiversity loss (IPBES 2019). While these five global perturbations are typically studied independently, there is increasing recognition that they form a complex, interrelated web requiring broad interdisciplinary management approaches. Recent analyses have found that the increase in the rate of new invasions shows no sign of saturation (Seebens et al. 2017), suggesting that more focused and effective policy and management programs will be required to both reduce invasion rates and identify mitigation strategies. CITES (2004) has further supported regulations relative to the spread of NIS through international trade.

In South America, our knowledge of the history, diversity, and impacts of marine bioinvasions is limited. Recent comprehensive work is limited to an assessment of marine NIS diversity in Argentina-Uruguay (raising the number of recognized invasions in those countries from 29 to 129 species; Schwindt et al. 2020) and in Ecuador's Galápagos Islands (raising the number of recognized invasions from 5 to 53 species; Carlton et al. 2019). For Chile, Castilla et al. (2005) and Castilla and Neil (2009) listed 23 marine NIS, and Villasenor-Paradaet al. (2018) added an additional 10 non-indigenous marine algae found in Chilean waters. Limited inventories of selected marine NIS are available for Venezuela (Perez et al. 2007; Figueroa and Brante 2020) and Brazil (Ferreira et al. 2009; Lopes 2009).

Some of these countries have advanced the creation of instruments for the management and public policy of bioinvasions. Chile (Comité Operativo para el Control de las Especies Exóticas Invasoras 2014), México (Comité Asesor Nacional sobre Especies Invasoras 2010), and Brazil (Ministério do Meio Ambiente 2018) have "national strategies" for the management of bioinvasions, including an "action plan" and "implementation plan" for Chile and Brazil respectively. Argentina and Perú are in a final revision process of a national strategy (personal communication, Evangelina Schwindt and Harol Gutierrez, 2022 respectively). Ecuador has a ten-year Action Plan for the prevention, management and control of exotic species in continental Ecuador (Ministerio del Ambiente 2019) and a strategy of Total Control of Invasive Species in the Galapagos Islands (Fondo de Inversión Ambiental Sostenible 2018). However, Uruguay (personal communication, Marcelo Iturburu, 2022) does not have overarching national strategies to embrace bioinvasion policy, although it has an operational tool, "Response Protocol to

Invasive Alien Species", prepared by the Committee on Invasive Alien Species (CEEI) and based on a framework document "General Coordination Protocol of the National Emergency System during the Response to Emergencies and Sudden Disasters" (CEEI 2018).

Because substantial gaps appeared to remain in Chile relative to our understanding of the diversity, distribution, impacts and management of marine NIS, and because of challenges relative to both inter- and intra-agency and institutional coordination and information exchange, a workshop on the "*Past, Present and Future of Marine Bioinvasions in Chile*" was held in October 14-15, 2019 at the Universidad Católica del Norte in Coquimbo. The workshop brought together national and international experts to discuss NIS science and management and to provide a platform for mapping out a potential research and policy agenda. Workshop participants represented five countries (Argentina, Chile, Ecuador, Uruguay, and the United States), including 22 researchers from 10 institutions, and 16 administrators and government service workers from five Chilean agencies. Participants brought to the workshop expertise in invasion biology and biosecurity, marine science, marine policy and management, and public education and outreach. The workshop Agenda, revised to reflect the final presentations, is shown in Supplementary material Appendix 1.

The workshop began with literature-derived overviews of the status of marine bioinvasion science, broad latitudinal patterns of invasions in the Eastern Pacific Ocean, invasion vectors, invasions in biofouling communities and in Marine Protected Areas, NIS algae in Chile, and early detection and rapid response strategies to invasions. Also discussed were economic and social perspectives on NIS. A second main topic focused on NIS management in Chile, relative to international and national governance, including opportunities for inter-institutional coordination. In a final block, the participants divided into three working groups to discuss knowledge and knowledge gaps and the strategies and resources required to advance NIS research, policy, and management. Throughout the workshop participants were asked to complete a two-part voluntary survey to determine their current primary work focus and to assess their opinions relative to where resources should be allocated.

In order to provide a basis of present knowledge and future perspectives for the monitoring of marine NIS in Chile, we summarize here the results of the surveys and the workshop, supplemented by selected literature updates.

Surveys results: Conference Attendees Field of Work and Assessment of Chilean NIS Needs and Priorities

From the 61 people (including students, visitors, and observers) that attended the symposium, a total of 38 people completed the surveys (Appendices 2 and 3). Participants were first asked to identify their organization and, from a pre-constructed set of choices, their priorities for Chile relative to marine bioinvasions.

Table 1. First and second topics that each participant declared as their main field of work.

	Field	Public Service (n = 16)	Research (n = 22)	Total
Primary field of work	Research	3	21	24
	Management and Administration	9	1	10
	Public Policy	4	0	4
Secondary field	Education and Outreach	2	7	9
	Management and Administration	2	0	2
	Public Policy	8	0	8
	no field chosen	4	15	19

Table 2. Attendees' assessment of Chilean NIS needs and priorities.

Subject	Attendee Background		Total
	Public Service	Research	
Research	5	9	14
Biosecurity	4	5	9
NIS management	2	3	5
Improvement of collaborative networks	2	2	4
Public policy	1	2	3
NIS prioritization list	1		1
Education and outreach	1		1
No subject identified		1	1

Sixteen respondents from public services identified themselves as representing managers and administrators (n = 9), public policy (n = 4) and research (n = 3). Twenty-two attendees from academic and research centers identified themselves as researchers (n = 22) or in management and administration (n = 1). None declared outreach or education as a main focus, although it was considered the second choice for 9 attendees (2 from public services and 7 from academia) (Table 1).

Relative to their knowledge on bioinvasions, six respondents identified themselves with a "lot" of knowledge, and 22 with "medium" knowledge. Meanwhile, 7 attendees declared to have "little" knowledge of bioinvasions, and 3 stated they had no knowledge of bioinvasions. Participants were next asked to identify the "needs and priorities for NIS for Chile." Responses were grouped into 7 major themes (Appendix 4). Of the 38 respondents, 36,8% (n = 14) identified research-related topics as the main priority (9 were researchers) and 23,7% (n= 9) identified topics related with biosecurity (5 researchers and 4 managers) (Table 2).

Finally, attendees were asked to define the priority to address bioinvasion in Chile, in scale 1 to 10, being 1 lowest priority and 10 the highest priority. Thirty-two attendees declared that bioinvasion are among 8 to 10 of priority, five allocate priority among 3 and 7, and none of them declared priority between 1 and 2. One did not answer the question.

Knowledge and Knowledge Gaps: The current status of marine NIS knowledge in Chile

Based upon careful assessments of the published literature, workshop participants discussed the current status of knowledge in Chile of marine NIS diversity, distribution and ecological and economic impacts, as well as

NIS management, including the status of knowledge of those vectors that may continue to actively introduce new NIS to Chilean waters.

Status of Knowledge of Marine NIS Diversity and Distribution

The workshop concluded that our understanding of the diversity and distribution of non-indigenous (and cryptogenic) marine species in Chile's continental and island coastal waters is extremely limited. As noted above, Castilla and Neil (2009) and Villasenor-Parada et al. (2018) listed a total of 33 marine NIS as established in Chile.

While recent literature often repeats that Castilla and Neil (2009) reported 51 introduced marine species on the Chilean coast (for example, Manríquez et al. 2014), more than half of these species occurred only in enclosed aquaculture facilities, were not established, or are no longer considered introduced (Gorski et al. 2017; Villasenor-Parada et al. 2018; J. T. Carlton, personal communication). Fuentes et al. (2020), in an extensive multi-taxa, multi-habitat (freshwater, marine, and terrestrial) inventory of NIS in Chile, restricted their marine invertebrate coverage to mollusks and polychaete worms, resulting in reporting only 12 introduced marine invertebrate species established in Chile. However, of these 12 species, one (the bivalve *Perna perna*) does not occur in Chile (Perez 2014), six are not known to exist as reproducing populations (the scallop *Pecten maximus*, the seaslug *Aplysia juliana*, the whelks *Monoplex wiegmanni* and *M. keenae*, and the polychaete worms *Terebrasabella heterouncinata* and *Polydora hoplura*), and one is a native species (*Polydora bioccipitalis*) (Radashevsky and Olivares 2005; Ashton et al. 2008; Moreno et al. 2006; Araya 2015; Radashevsky and Migotto 2017), leaving what would appear to be only four introduced marine mollusks and worms established in the entire country.

In other recent work, Pacheco and Andrade (2020) concluded that none of the 91 taxa they found in Antofagasta Bay in beds of the native mussel *Perumytilus purpuratus* and of the non-native ascidian *Pyura praeputialis* were introduced, although 46.5% of their taxa were not identified to species level, and despite the presence of other invaders, including *Pyura*, and the non-native seaweed *Codium fragile fragile* in the Bay (but the latter not found in the mussel bed or ascidian bed samples).

An additional example reflecting a need for greater understanding of the status of marine NIS in Chile is the recent work of Darrigan et al. (2020), who report that the Pacific oyster *Magallana gigas* has "the greatest distributional range in South America" of any non-native marine mollusk, being "recorded in six marine ecoregions". Three of these ecoregions are reported as being in Chile. Darrigan et al. (2020) comment that "the information about the species and its impact is scarce. There are not enough studies on the impact over the native communities and ecosystems". However, to our knowledge, *C. gigas* does not form naturally reproducing oyster beds in Chile, and thus

exists primarily only in mariculture farms, even as Darrigan et al.'s (2020) map provides a compelling picture of the apparent large scale of invasion of Chile by a non-native oyster.

Overall, and in concert with the critical recent reassessments noted above of NIS diversity in Argentina/Uruguay (expanding the list from 29 to 129 species) and in the Galápagos Islands (from 5 to 53 species), the diversity of marine NIS in Chile has likely been substantially underestimated. Carlton (2009) and Carlton and Fowler (2018) have underscored the potential for both the historical and modern-day underestimation of the number of non-native species in most countries, and Chile may be no exception. Castilla and Neill (2009) noted that Chilean coastal waters have been exposed to global shipping for over 500 years, including intense periods of visits of international fleets involved in the whaling, guano, and nitrate industries in Chile in the 19th and 20th centuries. In addition, Chilean aquaculture industries have long imported exotic fish (especially salmonids) and shellfish (such as abalones and oysters) for the aquaculture industry. A preliminary re-evaluation of Chilean marine biodiversity literature since the mid-1800s, combined with detailed scrutiny of the global biogeography of selected examples of harbor and estuarine species across multiple phyla suggests that, in contrast to the above assessments, at least 100 marine NIS are established in Chile (J. T. Carlton, *personal communication*, and *in preparation*).

Finally, workshop participants discussing NIS diversity knowledge and knowledge gaps strongly emphasized the fundamental need to significantly enhance Chile's human resources for taxonomic expertise for marine invertebrates and seaweeds. Identified were the lack of Chilean experts for many invertebrate and algal groups and the need to develop strategies to incentivize students to enter the field of taxonomy and systematics. Participants identified productive strategies going forward that would include developing training courses with international collaborators; significantly increasing job opportunities for systematists at museums, universities, and other research centers; strengthening the resources at the National Museum of Natural History, and linking taxonomy (and thus taxonomists) with issues of biosecurity (Appendices 5, 6).

Status of Knowledge of Marine NIS Ecological and Environmental Impacts

Only a few studies were found to document the ecological and environmental impact of invasions in Chile's coastal waters, a conclusion foreshadowed more than a decade ago by Castilla and Neill (2009) who noted that "evidence regarding the ecological effects of NIS in Chile is scarce".

The Australian seasquirt *Pyura praeputialis* in Antofagasta Bay, which supports a local fishery (discussed below), was found to have significantly altered rocky intertidal community structure (Cerda and Castilla 2001; Castilla et al. 2004a), including outcompeting the native mussel *Perumytilus*

purpuratus in the middle and low intertidal (Castilla et al. 2004b). Pacheco and Castilla (2000) found that the white oystercatcher (*Haematopus palliatus pitanay*) and the black oystercatcher (*H. ater*) prey on *Pyura praeputialis* in the Bay of Antofagasta. This predation, along with food harvesting of *P. praeputialis* by pyura-gatherers, subsequently significantly reduced its abundance (Castilla et al. 2014; Manríquez et al. 2016), thus reversing its impact and returning the shore to a presumed more pre-*Pyura* state. In effect, harvesting of *P. praeputialis* accomplished an effective large-scale eradication of this species. Of interest is that Soto et al. (2001) similarly discussed artisanal fishing as a mechanism of control of introduced fish, in this case escaped salmon. In contrast, Castilla et al. (2014) noted that *Pyura* beds, by providing a three-dimensional habitat, also increased local diversity, leading (among other effects) to enhanced populations of other harvestable edible species, including octopus and the loco ("Chilean abalone"), the gastropod *Concholepas concholepas,* an active predator of *Pyura* beds. Recent work (Pacheco and Andrade 2020) has established that the invertebrate diversity in native *Perumytilus* beds, however, rivals that of the introduced *Pyura* beds.

The Australian seagrass *Heterozostera nigricaulis* is another important bioengineer, having been documented in Tongoy Bay as a significant primary producer (Ortiz and Wolff 2002). In contrast, the Japanese green seaweed *Codium fragile fragile* can be an important fouling pest impacting the seaweed *Gracilaria* aquaculture in Chile, resulting in significant losses (Neill et al. 2006), while the Japanese seasquirt *Ciona robusta* flourishes on suspended artificial structures (Dumont et al. 2011) and can also be a dominant biofouler and thus significant pest impacting scallop aquaculture operations in Chile (Uribe and Etchepare 2002; Jofré-Madariaga et al. 2014; personal observations).

Neill et al. (2020) found that the exotic marine boring worm *Polydora rickettsi* was the competitively dominant species over native boring polychaetes in commercial oyster shells. Valdivia et al. (2005); Dumont et al. 2011; Krüger et al. 2018; Leclerc et al. (2020); Figueroa et al. (2021) and LeClerc et al. (2021), among others, have considered the relative roles of non-indigenous marine species in influencing and structuring marine fouling communities in Chilean ports and harbors.

The impact of introduced predators has been noted by Navarrete and Castilla (1993), who found that Norway rats (*Rattus norvegicus*) consumed 38 different prey species in a marine reserve in Las Cruces, including snails, clams and mussels, chitons, barnacles, crabs, seastars, sea urchins, and fish, and may have particularly important effects on intertidal snails and crabs.

The current understanding of the mechanisms and magnitude of the impact of non-indigenous phytoplankton in the marine ecosystems of Chile is still limited, nor is there a clear picture of which phytoplankton

species already present in Chile may be introduced or cryptogenic. Until 1995, little information was available about the composition and distribution of the planktonic component of the vast austral channel and fjord system. Although the number of studies has increased significantly in the last decades, the focus of research has been mainly on monitoring harmful algal blooms (HAB) in inland waters of the regions of Los Lagos, Aysén y Magallanes (Avaria 2008). Nevertheless, the prediction of the occurrence of marine planktonic blooms and the associated risks and impacts of non-indigenous phytoplankton species on ecosystem services and biodiversity are still limited in the country (Sandoval et al. 2018). However, the blooms occurring in northern Patagonian waters in recent years have exhibited an unprecedented extent and intensity, suggesting a connection with the Ecuador (ENSO) and Subantarctic (SASW) regions and anthropogenic climate change (León-Muñoz et al. 2018). We note below the blooms of certain phytoplankters relative to potential economic impacts.

Overall, workshop participants identified a critical need to assemble the information on Chilean marine NIS published both in peer-reviewed literature and government reports; flagged a lack of historical knowledge of marine NIS in Chile, and a lack of standardized protocols by which to sample NIS and by which to assess their impacts. To address these challenges participants proposed selecting one or more "model NIS" upon which to develop standardized impact assessment criteria; greatly increase sampling of marine and estuarine communities for NIS, and increase monitoring capacity of NIS species, and continue to address revising biosecurity protocols (Appendix 5).

Status of Knowledge of Marine NIS Economic Impacts

There appear to be no studies in Chile that quantify the positive or negative economic impacts of marine NIS in Chile, although some impacts have been qualitatively reported. Here we consider those NIS that are established as wild populations in Chile, and not species that are solely or largely maintained in farms, such as the Japanese oyster *Crassostrea gigas* and the California red abalone *Haliotis rufescens*.

Neill et al. (2006) reported on the invasion of the Japanese alga *Codium fragile fragile* in Chilean *Gracilaria* seaweed farms, noting that, "Since the introduction of *C. fragile*, red algae farmers must invest additional time and money in removing this pest, which becomes entangled in the thalli of *Agarophyton chilensis* [= *Gracilaria chilensis*] and pulls the red alga off the bottom before it can be harvested by divers", and that, "Since weedy species generate a great loss of time and money in *G. chilensis* farms, it is likely that without intervention, the costs associated with the *C. fragile* invasion threaten the persistence of *G. chilensis* farms in northern Chile". However, the actual economic impact (in terms of lost time and lost product) appears to not have been calculated.

Fouling NIS such as *Bugula neritina* and *Ciona robusta* build dense biomass on suspended aquaculture requiring regular cleaning of these structures, and while economic costs have not been quantified ecological strategies to reduce these impacts have been tested (Dumont et al. 2009).

Castilla et al. (2005) and Castilla and Neill (2009) noted that the NIS red alga *Mastocarpus latissimus* (= *M. papillatus* of earlier Chilean literature), known as "luga gallo", is harvested by seaweed collectors and was of commercial importance, but we have not found economic evaluations of this fishery. Similarly, the Australian seasquirt *Pyura praeputialis* has been harvested in Antofagasta Bay (Castilla et al. 2014) but there also appears to be no formal assessment of the value of this fishery.

In 2015 at least 343 whales were found dead in the south of Chile, due to the consumption of the "prawn of the channels" (the munnid anomuran *Grimothea gregaria*) contaminated with HAB (Häussermann et al. 2017). Then, in early 2016, a bloom of the cryptogenic dictophyte *Pseudochattonella* spp. caused mortalities of salmonids of the order of 40,000 tons in Chiloé. Subsequently, in April of the same year, one of the largest blooms events of the cryptogenic dinoflagellate *Alexandrium catenella* occurred in the south of Chile. It extended about 400 km from the zone initially affected, interrupting the extractive activity, and turning the Chiloé Archipelago into a zone of environmental, social, economic and health catastrophe without precedent in the region (Armijo et al. 2019).

Metridium senile is a non-native sea anemone first reported in Chilean Patagonia in 2005 (Haüssermann et al. 2006; Haüssermann and Försterra, 2005) and has since extended its distribution in the benthos in fjords and channels. Haüssermann et al. (2022) and Molinet et al. (2023) reported the detection and expansion of this anemone in large tracts of benthic substrate in north-western Patagonia, threatening both benthic communities and important commercial resources such as the edible sea urchin *Loxechinus albus*.

Workshop participants described as one of the main challenges the lack of standardized national NIS economic impact studies and the concomitant need to have experts develop those studies. To address this challenge participants proposed to select as models high profile marine NIS and with the engagement of scholarly economic expertise, underlain by a close collaboration among government, industry, and scientific experts, estimate their economic impact. One example suggested was to attempt to rigorously estimate the economic costs of NIS biofouling in Chilean aquaculture production, such as in scallop and oyster farms (Appendix 5).

Status of Knowledge of Marine NIS Management: Established Species and Vectors

Workshop participants were not able to identify any known coordinated nationwide programs in Chile focused on the control and management of established non-indigenous marine species. Moreno et al. (2006) discussed

the need for the potential control of non-indigenous boring polychaetes in Chile relative to their threat to commercial mollusk species. Neill et al. (2006) proposed that control of the non-indigenous seaweed *Codium fragile fragile* by mechanical, chemical, or other means be considered. The workshop recognized that there are Chilean initiatives and research groups to address, for example, the distribution and impacts of free-living non-native salmonid populations in Chilean aquatic ecosystems, as well as in ocean ecosystems, where chinook salmon appear to be established, but coho and Atlantic salmon are not (Soto et al. 2023).

Castilla et al. (2014) and Manríquez et al. (2014) raised the question (relative to the harvesting of the edible non-indigenous seasquirt *Pyura praeputialis*)—a question yet to be addressed in Chilean policy and management—as to whether accidentally introduced species that may provide ecosystem services (such as directly or indirectly providing fisheries resources) should be protected under a regulatory framework.

Relative to future invasions, participants were not aware of any current inventory of the vectors (and the species that might be associated with them) that may introduce new marine species to Chile, including disease agents, parasites, protists, invertebrates, algae, seagrasses, and fish. In other countries, such vectors may include (1) commercial ships and transoceanic recreational vessels, carrying species in ballast water and on the hull or other niche areas as fouling organisms, (2) aquaculture, (3) the live bait trade, (4) the live seafood trade, and marine debris (Carlton 2001; Williams et al. 2013, Carlton and Ruiz 2015; Fowler et al. 2016; Carlton et al. 2017). Astudillo et al. (2009) have detailed the potential importance of detached aquaculture buoys in Chile acting as prospective dispersal agents.

Relative to ballast water and hull biofouling, Chile has 39 international ports. In 2020, there were 5.313 international ship arrivals (Figure 1), with the busiest ports being Mejillones (n = 776), San Antonio (n = 774) and Valparaiso (n = 547). Chile receives international vessel traffic from at least 66 different countries (Figure 2). The top 9 countries in 2020 were USA (23%), Colombia (13.8%), China (10.6%), Brazil (8.1%), Argentina (6.6%), Ecuador (5.4%), Australia (4.6%), Canada (4.5%) and Perú (4.5%), representing 81.1% of total tons imported. At this time there are no precise data on the amount of unexchanged or untreated ballast water released in Chile, and the amount of ballast water released may vary considerably over time, by vessel type and size, and by commodity load.

The United Nations International Convention for the Control and Management of Ships' Ballast Water and Sediments was adopted on 13 February 2004 and entered into force on 8 September 2017. While Chile is not yet a signatory to the Convention (https://www.imo.org/en/About/Conventions/Pages/StatusOfConventions.aspx), Chile's Ballast Water Management Plan is in line with Convention requirements and includes

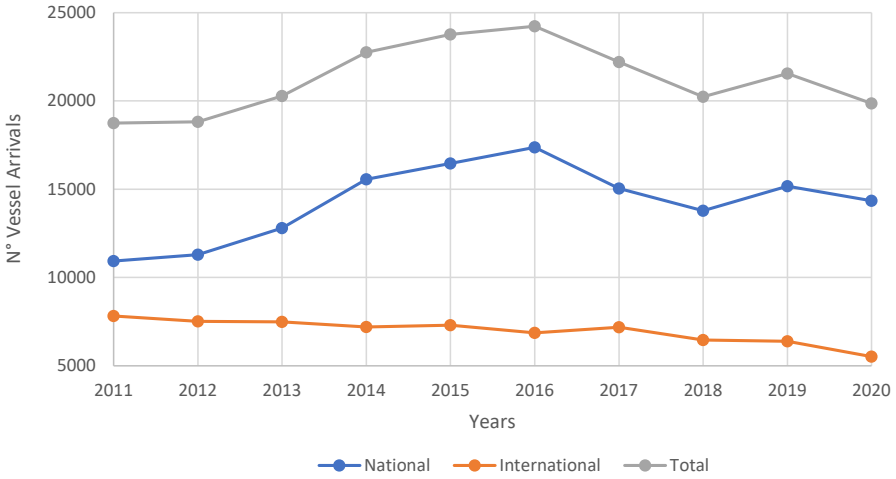

Figure 1. Vessel arrivals at all Chilean ports between 2011-2020. Data from "Boletín Estadístico Marino – Edición 2021", Armada de Chile (2021).

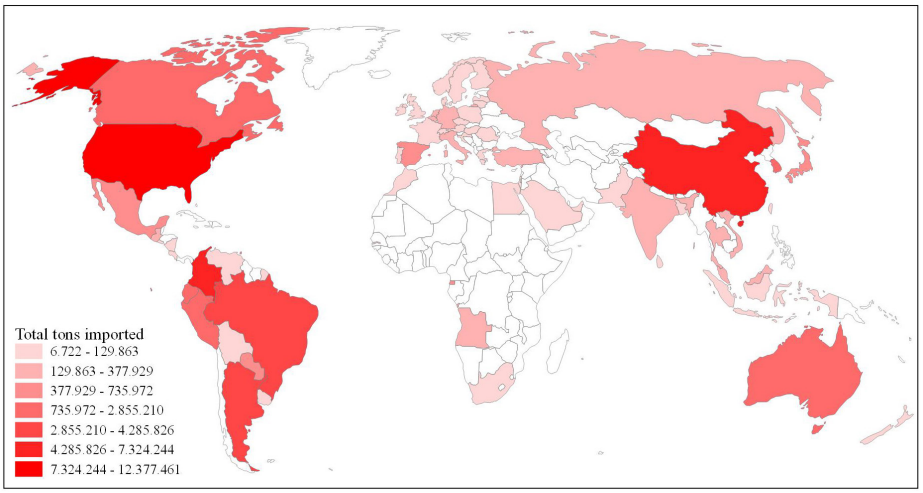

Figure 2. Global map of imported tonnage by international ship arrivals at all Chilean ports in 2020. The scale of colors represents the relative tonnage. Data from "Boletín Estadístico Marino – Edición 2021", Armada de Chile (2021).

ballast water exchange requirements for "All ships coming from abroad and ballasted with sea water (and) all ships coming from zones affected by cholera or by any similar contagious epidemic" (Lloyd's Register 2019). Chile participated in the international United Nations GloBallast Program (https://www.imo.org/en/OurWork/PartnershipsProjects/Pages/GloBallast-Programme.aspx, accessed September 2023). The national focal point and project coordination for ballast water management in Chile lies with the Armada de Chile's Direccion General del Territorio Maritimo y de Marina Mercante (DIRECTEMAR) (http://archive.iwlearn.net/globallast.imo.org/cpps/chile/index.html, accessed September 2023).

Relative to established NIS and their potential management, workshop participants identified the major challenges as including the capacity to detect and recognize non-indigenous species and to identify the responsible agencies accountable for NIS monitoring. To address these challenges participants

identified the need for a formal national monitoring and management plan. Intimately involved would be representative stakeholders at local, regional, and national levels (Appendix 5).

Status of Marine NIS National Policy

In 1994, Chile ratified its commitment to the Convention on Biological Diversity (CBD) through which Law 19,300 was created in Chile, and with it the National Environment Corporation (CONAMA), which became the Ministry of the Environment in 2010. That same year, the CBD urged the parties to update their National Biodiversity Strategies in accordance with the "Strategic Plan for Biodiversity 2011-2020 and the Aichi Targets". During the Conference of the Parties N°15 (COP15) held in Canada in December 2022, the Kunming-Montreal Global Biodiversity Framework (GBF) was adopted. The GBF has 23 targets, where the Target 6 focuses on Invasive Alien Species.

Along with the adoption of the GBF, countries agreed to update their National Strategy of Biodiversity. In Chile, the National Strategy of Biodiversity is led by the Ministry of Environment of Chile. The strategy has, among its 6 thematic areas, one focused only on bioinvasions, and two others, Conservation of Marine Biodiversity, and Oceanic Islands and Protected Areas, where non-indigenous species are part of their goals and activities. This national policy has a timeframe of 2017–2030. The bioinvasion thematic area was built along with other public services that have mandates relative to terrestrial and marine non-indigenous species management and/or biosecurity. To advance the bioinvasion thematic area, an Operational Committee for the Prevention, Control and Eradication of Invasive Alien Species (COCEI) was created in 2015 to be led by the Ministry of Environment of Chile and composed of 13 public agencies (Ministerio del Medio Ambiente, Ministerio de Relaciones Exteriores, Subsecretaria de Pesca y Acuicultura, Servicio Nacional de Pesca y Acuicultura, Corporación Nacional Forestal, Servicio Agrícola y Ganadero, Oficina de Estudios y Políticas Agradas, Dirección de Territorio Marítimo y Mercante, Carabineros de Chile, Policía de Investigaciones, Subsecretaría de las fuerzas Armadas, Servicio Nacional de Aduanas, and Museo Nacional de Historia Natural).

In September 2023, the law that creates the biodiversity and protected areas service was published in Chile (Ministerio del Medio Ambiente, Ley 21.600 de 2023, 6 septiembre 2023). This Law, together with completing the environmental institutional framework for the country, will establish strategies to prevention, control and eradication of exotic and "invasive" species, permitting the generation of lists of species to be addressed, and the creation and execution of management plans in marine and continental environments, both inside and outside protected areas.

Currently, in Chile there are two public services at the national level with direct oversight of work with marine bioinvasions, the Undersecretariat of

Fisheries and Aquaculture (SUBPESCA) under the Ministry of Economy and the General Directorate of Maritime Territory and Merchant Marine (DIRECTEMAR) which is part of the Chilean Navy and is under the Ministry of National Defense. SUBPESCA determines, publishes and updates annually the "List of Living Hydrobiological Species Authorized to Import". In its 2021 publication, the importation of 10 species of salmonids for farming in open and semi-closed systems (Res.Ex.2266, SUBPESCA 2022) is permitted. DIRECTEMAR has two relevant circulars. Maritime Circular A-51/002 was published in 2012 with the objective to establish procedures and provide recommendations for the adoption of preventive measures to minimize the risks of introduction of harmful aquatic organisms and pathogens by ships entering national ports. The objective of the second Maritime Circular, A-52/007 published in 2018, is to establish the conditions to authorize the underwater cleaning of vessel hulls in ports in contained conditions to minimize the introduction of pollutants (paint and species) to the marine environment (https://www.directemar.cl/directemar/intereses-maritimos/aguas-de-lastre-y-limpieza-de-casco).

Workshop participants identified the critical need to continue to develop national and international public policy where prevention of future incursions was the focus. The main challenges for national policy identified by attendees included trade-offs between industries impacted by prevention strategies and the need to reduce invasions, lack of knowledge of which NIS are already established and potential NIS that might arrive, and a lack of knowledge of which ecosystems and regions may be particularly vulnerable to new invasions. Overarching were concerns about which agencies had oversight and how and with whom collaborations could and would be established for effective national policy strategies (Appendix 5). The workshop participants further emphasized the need for internationally standardized monitoring approaches and the ratification by Chile of the of ballast water convention (Appendix 5).

Status of Marine NIS international network

At the international level, Chile is an associated country of the Permanent Commission of the Southeast Pacific (CPPS), an intergovernmental body that promotes and articulates international cooperation in maritime affairs. During the implementation of the GloBallast Partnerships project (2008–2018) sponsored by the International Maritime Organization (IMO), the Regional Strategy for Ballast Water management was designed. The CPPS was part of the Regional Task Force that was commissioned to update the Regional Ballast Water Strategy once GloBallast ended. Subsequently, in 2019, the IMO started the Glofouling Partnership project to reduce the risk of bioinvasions due to biofouling, with the CPPS overseeing and supporting the implementation of the project (2019 to 2023). Nevertheless, it is important to highlight that Chile's status as only an associated country means that Chile does not get training nor funding to address fouling management.

During the workshop to update the Regional Strategy for Ballast Water management, held on September 11 and 12, 2019 (Bogotá, Colombia), the delegates of the countries agreed to increase the scope of the strategy to, in addition to ballast water, include other maritime vectors that may bring non-native species with them, thus generating the Regional Strategy to Prevent and Reduce Risks and Effects of the Introduction of Exogenous Marine Species in the Southeast Pacific, whose objective is to support the countries of the Southeast Pacific to implement the IMO guidelines and other international instruments in matters of marine bioinvasions.

The CPPS, along with updating the document, also made progress in the creation of a work plan and the formation of regional task groups to complete its operational structure, and where Chile already has its two representatives, DIRECTEMAR and the Ministry of the Environment.

Relative to international networking, workshop participants identified the lack of collaboration and communication as the main challenge to move forward. Attendees identified a need to systematically organize NIS knowledge in the same manner internationally in order to effectively share information across and between countries, and to continue to support and refloat international conventions as the main strategies to improve international networks (Appendix 5)

A Way Forward: Strategies and Resources Required to Advance NIS Research, Policy, and Management

In order to address the identified gaps in NIS knowledge and management, workshop participants envisioned an overarching national marine biosecurity strategy that would serve to address the current challenges of minimum capacities to approaching pressing issues, legislative and regulatory gaps, and challenges of inter-agency collaboration and communication.

(1) Establish a National Marine NIS Research Program

This research program, which could be established by the Ministry of Science, Technology, Knowledge and Innovation, and the Ministry of Environment of Chile in cooperation with DIRECTEMAR and SUBPESCA, would have 4 critical components:

*(A) **Which NIS are Here?:** The Chilean National Marine NIS Database*

A national marine NIS database should include a detailed inventory of all known non-indigenous and cryptogenic marine species in Chile and their up-to-date distributions. As emphasized in the workshop results above, fundamental to an effective national NIS database program is the ability to increase taxonomic expertise across many invertebrate and algal groups. An understanding of NIS diversity is strongly correlated with the availability (or lack thereof) of expert knowledge (Castilla et al. 2005, page 214; Carlton and Fowler 2018). Workshop participants strongly supported the need to

create well-supported and ongoing national taxonomic training curricula and workshops. Participants also supported the need to develop a platform with free and universal access of NIS baselines for Marine Protected Areas (MPAs). NIS baselines should be included in MPA management plans or if such baselines are already in place, these should be regularly and systematically reviewed.

(B) What are Their Impacts?: *National Research Program on Marine NIS Ecological, Economic, Societal and Cultural Impacts*

The workshop participants identified a pressing need for a nationwide research approach to understand the economic, environmental, ecological, societal and cultural impacts of those marine NIS established in Chilean national waters.

(C) How Are Species Arriving Every Day?: *A National Marine Vector Inventory*

Understanding the breadth and depth of the diversity of alien species that may be arriving on a daily basis in Chilean coastal systems is regarded as fundamental to an effective policy and thus management strategy. An inventory of the full suite of vectors that are now transporting marine NIS into Chilean waters is critical, accompanied by knowledge of which species are arriving by these pathways. Such vectors may include ballast water, vessel biofouling, aquaculture activities, marine debris, and other mechanisms.

(D) Which Future Arrivals Pose the Greatest Risks?: *A National Marine NIS Risk Assessment of Potential Future Invasions*

Given that many marine NIS now spreading around the world may be poised to enter Chile, a national risk assessment study should be established to identify the most high-profile probable future invaders, focused on potential source regions, and on which geographic regions and which habitats in Chile may be most vulnerable, including risks to Marine Protected Areas. This assessment would provide a "watch list" and the basis of a national EDDR Program (3, below).

(2) Establish a National Marine NIS Education & Outreach Program

Creating a unified national marine NIS education and outreach program to enhance citizen involvement and create a national flotilla of marine citizen scientists is fundamental to establishing a nationwide NIS monitoring and early detection network (below).

Some successful examples in Chile focus on introduced terrestrial species (https://www.schoolandcollegelistings.com/XX/Unknown/512282405785541/Naturaleza-Intrusa, https://noticias.udec.cl/naturaleza-intrusa-conociendo-a-los-enemigos-de-la-biodiversidad/, and https://ieb-chile.cl/noticia/naturaleza-intrusa-y-el-grupo-de-conservacion-de-la-guina-estuvieron-presentes-en-el-dia-de-la-fauna-chilena/). Naturaleza Intrusa (Laboratory of Biological Invasions

of the University of Concepcion) is a program for scientific outreach whose purpose is to raise awareness in the community about the impacts of terrestrial non-indigenous species that affect biodiversity and to publicize research and scientific advances on understanding invasions. A recent project on the iNaturalist platform gathers photographic records of large and visible marine invertebrate and seaweed NIS (https://www.inaturalist.org/projects/especies-marinas-invasoras-emi-chile-de82e066-306a-4636-be7b-c9c4edd887fe). Ocean-related programs in Chile include strong initiatives for beach clean-ups by DIRECTEMAR, Ocean Conservancy NGO, local communities and volunteers (https://www.beergeeks.cl/eventos/corona-y-parley-for-the-oceans-preparan-masiva-limpieza-en-playas-de-chile/, https://www.elmostrador.cl/generacion-m/2020/01/15/inicia-la-campana-anual-de-voluntarios-por-el-oceano-revisa-las-fechas-de-limpieza-de-playas-para-este-verano/ and https://www.directemar.cl/directemar/intereses-maritimos/limpieza-de-playas/limpieza-de-playas), but Chile lacks at this time a broad national education and outreach program on marine bioinvasions and their impacts. Such a program could be supported by the Ministry of Education and the Ministry of Environment, in cooperation with DIRECTEMAR, SUBPESCA, schools, and universities. Also to be closely involved would be public stakeholder groups who invest extensive time in marine waters, such as artisanal fishermen and recreational divers, as proposed by Hermoso et al. (2021).

Workshop participant highlighted the lack of knowledge by citizens on NIS and their impacts as a major gap. Participants proposed the design and implementation of increased communication, education and outreach, including incorporating the topic of NIS in school curricula (Appendix 5).

(3) Establish a National Marine NIS Monitoring and Early Detection-Rapid Response (EDRR) Program

A *National Marine NIS Monitoring Program* should be established to detect new invasions and to monitor changes in the distribution of established invaders, such as might result from climate change, habitat changes, or changes in anthropogenic coastal vectors. An N*IS Early Detection Network*, involving multiple agencies and institutions, and especially involving citizen scientists (see above), and focused specifically on a "watch list" of high-profile potential invaders (based upon 1 (D), above), will be critical to implementing modern *Early Detection – Rapid Response* (EDRR) strategies, which would include capacity building, communication systems, the ability for rapid and accurate species identifications (such as may be facilitated by *i-Naturalist*), and incident command systems (Meyerson and Simberloff 2020). Critical players in these initiatives include the Ministry of Environment and its advisory committee (SUBPESCA and its departments and sections, Aduanas, Army, and academic researchers).

(4) An Overarching National Marine NIS Policy

Supporting all of the above would be an overarching *National Marine NIS Policy* which would include components such as, a vector inspection program at points of arrival, rapid response to newly detected invader populations when and where possible, and species impact mitigation where and when possible. Implementing national NIS marine biosecurity policies should acknowledge and be sensitive to indigenous, local, and regional stakeholder interests and concerns.

As noted earlier, Chile currently has a National Biodiversity Strategy, which considers bioinvasions as one of its central axis, and which must be complied with through COCEI. In order to advance these goals, COCEI is setting up an Advisory Committee, where leading national and international researchers will take part. One of its main short-term objectives is to generate a prioritized list of non-indigenous species of concern in order to begin to identify the research needed to set management guidelines.

In Figure 3, we summarize the essential key elements of a Marine NIS National Biosecurity Agenda, which would form the bases of a National Marine NIS Policy for Chile. National policy is anchored by interdisciplinary, multi-institutional collaborative networks working closely in concert with international strategies to produce the most effective outcomes relative to managing the prevention, spread, and impact of non-indigenous aquatic species. Major components include national databases, vector inventories, risk assessments, monitoring programs, and research programs, which must be supported by a strong national taxonomic and biodiversity training program and successful public education and outreach initiatives.

Discussion and conclusions

We are not the first to propose a need for the development of strategies and programs to address marine non-indigenous species in Chile. In 1996 Buschmann et al. (1996) called for research on the "effects of the introduction of new species" in Chile. In September 1998 a meeting was held in Viña del Mar to consider the current status of positive and negative impacts of exotic species introductions in Chile. This meeting, "La reunión de expertos para analizar los efectos ecológicos de la introducción de especies exóticas en el Pacífico Sudeste", (http://biblioteca.culturaypatrimonio.gob.ec/cgi-bin/koha/opac-detail.pl?biblionumber=15383; accessed November 2022), included a synoptic table of species introduced in Chile, Colombia, the Galapagos Islands (Ecuador), Panama, and Peru, but did not distinguish between established species and those imported for food, ornamental, or other purposes. The table was reprinted by Letelier (1999) in a paper focused on the question of the intentional introduction of marine molluscs in Chile, especially the California red abalone *Haliotis rufescens*, with considerations as to what the impact would be on the natural environment if the red abalone were to become established in the wild in Chile.

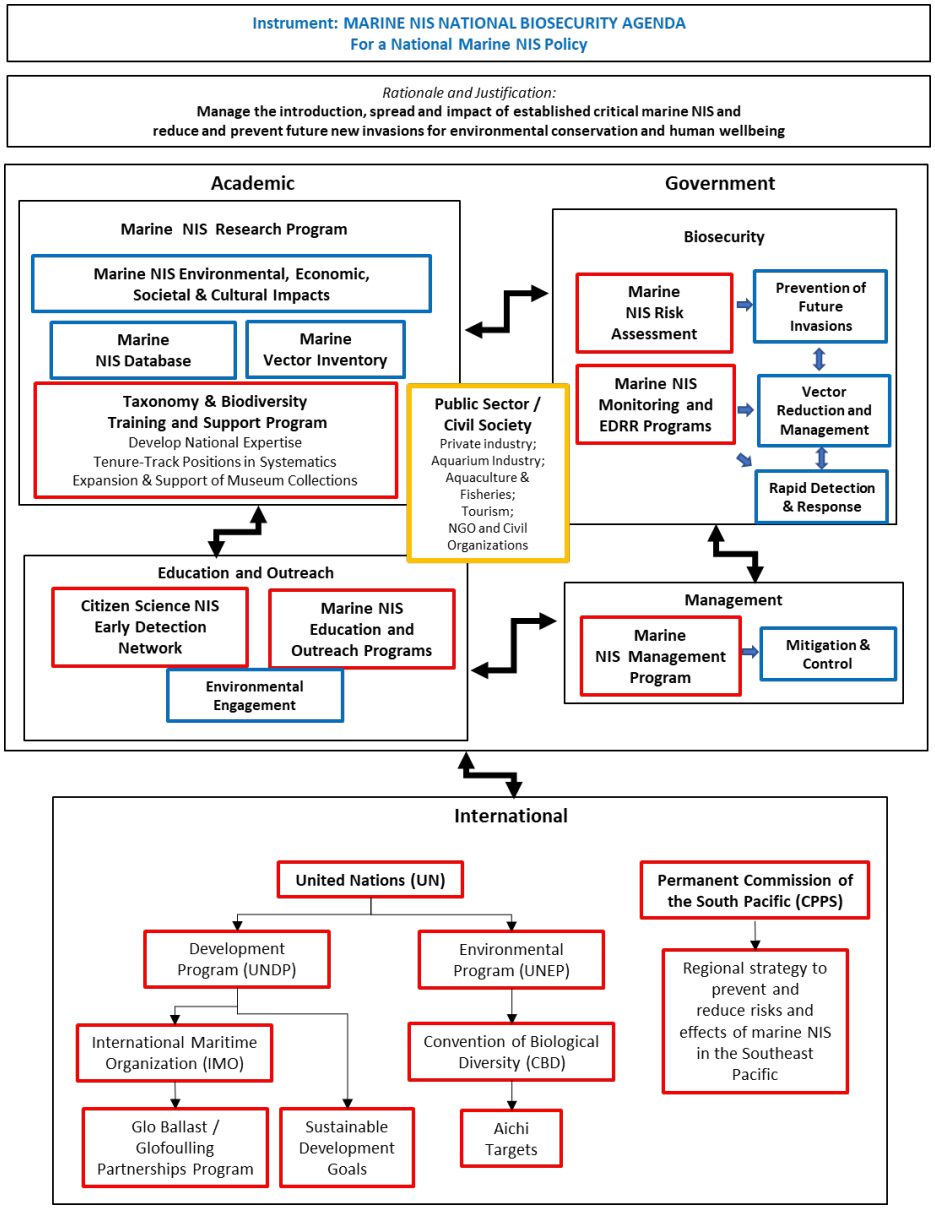

Figure 3. A summary flow diagram outlining the key elements of a National Marine NIS Biosecurity Agenda, which would form the basis of a National Marine NIS Policy for Chile.

Camus (2005) expressed concern about the scale of the introduction of exotic marine species in use in Chile for aquaculture, as well as "the accidental or intentional introduction of any native species in Chile, to any environment where it is not present due to natural causes". Camus noted that, "National and international regulations appear to be insufficient or ineffective in regulating these activities, and may even be in conflict with larger economic interests". Finally, Camus urged that, "It would be desirable for the Chilean marine biology scientific community to take a clearer position on the problem, since aquaculture is beginning to be seen as a discipline in conflict with conservation", with Castilla et al. (2005, page 227) in the same year making a similar observation.

Castilla and Neill (2009) again reviewed marine NIS regulations in Chile, emphasizing that "there are no specific monitoring programs that aim to

evaluate the presence of NIS in susceptible coastal areas (e.g. in and near shipping ports and aquaculture facilities", noting that "inadequacies in the national legislation leaves Chile open to potential problems of marine NIS biosecurity". They concluded that "it is essential for Chile to implement preventive measures, including monitoring programs to survey NIS hotspots (e.g. docks and pilings, aquaculture facilities, fishing equipment, areas within and near ports, bays and estuaries), as well as baseline evaluations in susceptible areas, to detect NIS introductions early on and determine propagule pressure. Proactive legislation to control the entrance of NIS to Chile should focus on primary introduction pathways and principal donor areas, as well as identify species that are likely to become pests. In cases where marine NIS have already been introduced into the system, researchers and managers should conduct studies to evaluate ecological and socio-economic impacts".

Now, more than a decade later, we renew the calls-to-arms by the above workers, and further propose that critical advancements must be made by the establishment of a clear, focused blueprint and roadmap for national marine NIS programs.

We close with an observation concerning the communication in Chile between those in the policy and management world and academic research. Information produced in these arenas, often acting as silos, is not fully reaching the other. Academic researchers publish in peer-reviewed journals largely in English.

A 2021 ranking carried out by EF Education First (EF-EPI 2021), places Chile 47th out of 112 countries with a "moderate" command of English and seventh in comparison to other countries in Latin America. The study gives an English command score of 516 for Chile, placing it in category B2 (500–599), characterized as the capacity for understanding the main ideas of complex texts, as long as they are within the field of specialization of the reader. These results suggest that research data published in English (in journals that further may not be readily accessible or open access) may be reaching manages in low proportion if at all. On the other side of the ledger, government reports are referred to as "gray literature", may be perceived (correctly or incorrectly) as not peer-reviewed and are rarely cited by researchers in journal papers, and are thus omitted or ignored as potentially available information. In this way, the information produced by researchers may not benefit decision makers, and the knowledge and needs of the government are not being integrated into academic research. We urge researchers to more inclusively and carefully consider pertinent government reports, while at the same time we urge government agencies to increase the availability and accessibility of government documents.

For a strong and effective "way forward", we suggest that this situation represents another critical gap that could and should be effectively, urgently, and clearly addressed in national strategies going forward. Regular meetings

bringing together professionals from government agencies, companies and academia, such as this one conducted in October 2019 in Coquimbo, Chile, could be the way forward and should be held on a regular basis.

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Conflict of interest/Declaration of interests

Five of the authors are employees of the Government of Chile, but declare no conflict of interest relative to any financial, personal, or other relationships that inappropriately influence, or be perceived to influence, this work.

Authors' contributions

All authors participated in the workshop and contributed to the present paper.

References

Araya JF (2015) Current status of the non-indigenous molluscs in Chile, with the first record of *Otala punctata* (Muller, 1774) (Gastropoda: Helicidae) in the country and new records for *Cornu aspersum* (Muller, 1774) and *Deroceras leave* (Muller, 1774). *Journal of Natural History* 49: 1731–1761, https://doi.org/10.1080/00222933.2015.1006703

Armijo J, Oerder V, Auger P-A, Bravo A, Molina E (2019) The 2016 red tide crisis in southern Chile: possible influence of the mass oceanic dumping of dead salmons. *Marine Pollution Bulletin* 150, https://doi.org/10.1016/j.marpolbul.2019.110603

Ashton T, Riascos JM, Pacheco A (2008) First record of *Cymatium keenae* Beu, 1970 (Mollusca: Ranellidae) from Antofagasta Bay, northern Chile, in connection with El Nino events. *Helgoland Marine Research* 62 (Supplement 1): S107–S100, https://doi.org/10.1007/s10152-007-0084-5

Astudillo JC, Bravo M, Dumont CP, Thiel M (2009) Detached aquaculture buoys in the SE Pacific: potential dispersal vehicles for associated organisms. *Aquatic Biology* 5: 219–231, https://doi.org/10.3354/ab00151

Avaria S (2008) Phytoplankton in the austral Chilean channels and fjordsin: In: Silva N, Palma S (eds), Progress in the oceanographic knowledge of Chilean interior waters from Puerto Montt to Cape Horn. Comité Oceanográfico Nacional, Pontificia Universidad Católica de Valparaíso. Valparaíso, pp 89–92

Buschmann AH, Lopez DA, Medina A (1996) A review of the environmental effects and alternative production strategies of marine aquaculture in Chile. *Aquacultural Engineering* 15: 397–421, https://doi.org/10.1016/S0144-8609(96)01006-0

Camus PA (2005) Introducción de especies en ambientes marinos chilenos: no solo exóticas, no siempre evidentes. *Revista Chilena de Historia Natural* 78: 155–159, https://doi.org/10.4067/S0716-078X2005000100011

Carlton JT (2001) Introduced species in U.S. coastal waters: environmental impacts and management priorities. Pew Oceans Commission, Arlington, Virginia, 28 pp

Carlton JT (2009) Deep invasion ecology and the assembly of communities in historical time. In: Rilov G, Crooks JA (eds), *Biological Invasions in Marine Ecosystems*. Springer-Verlag, pp 13–56, https://doi.org/10.1007/978-3-540-79236-9_2

Carlton JT, Ruiz GM (2015) Anthropogenic vectors of marine and estuarine invasions: an overview framework. In: Canning-Clode J (ed), Biological Invasions in Changing Ecosystems: Vectors, Ecological Impacts, Management, and Predictions. De Gruyter Open, pp 24–36, https://doi.org/10.1515/9783110438666-005

Carlton JT, Fowler AE (2018) Ocean rafting and marine debris: A broader vector menu requires a greater appetite for invasion biology research support. *Aquatic Invasions* 13: 11–15, https://doi.org/10.3391/ai.2018.13.1.02

Carlton JT, Chapman JW, Geller JB, Miller JA, Carlton DA, McCuller MI, Treneman NC, Steves BP, Ruiz GM (2017) Tsunami-driven rafting: Transoceanic species dispersal and implications for marine biogeography. Science 357: 1402–1406, https://doi.org/10.1126/science.aao1498

Carlton JT, Keith I, Ruiz GM (2019) Assessing marine bioinvasions in the Galápagos Islands: implications for conservation biology and marine protected areas. *Aquatic Invasions* 14: 1–20, https://doi.org/10.3391/ai.2019.14.1.01

Castilla JC, Neill PE (2009) Marine bioinvasions in the southeastern Pacific: status, ecology, economic impacts, conservation, and management. In: Rilov G, Crooks JA (eds), *Biological Invasions in Marine Ecosystems*. Springer-Verlag, pp 439–457, https://doi.org/10.1007/978-3-540-79236-9_26

Castilla JC, Lagos NA, Cerda M (2004a) Marine ecosystem engineering by the alien ascidian *Pyura praeputialis* on a mid-intertidal rocky shore. *Marine Ecology Progress Series* 268: 119–130, https://doi.org/10.3354/meps268119

Castilla JC, Guinez R, Caro AU, Ortiz V (2004b) Invasion of a rocky intertidal shore by the tunicate *Pyura praeputialis* in the Bay of Antofagasta, Chile. *Proceedings of the National Academy of Sciences* 101: 8517–8524, https://doi.org/10.1073/pnas.0401921101

Castilla JC, Uribe M, Bahamonde N, Clarke M, Desqueyroux-Faundez R, Kong I, Moyano H, Rozbaczylo N, Santelices B, Valdovinos C, Zavala P (2005) Down under the southeastern Pacific: marine non-indigenous species in Chile. *Biological Invasions* 7: 213–232, https://doi.org/10.1007/s10530-004-0198-5

Castilla JC, Manríquez PH, Delgado A, Ortiz V, Jara ME, Varas M (2014) Rocky intertidal zonation pattern in Antofagasta, Chile: invasive species and shellfish gathering. *PLoS ONE* 9, e110301, https://doi.org/10.1371/journal.pone.0110301

Cerda M, Castilla JC (2001) Diversidad y biomasa de macro-invertebrados en matrices intermareales del tunicado *Pyura praeputialis* (Heller, 1878) en la Bahía de Antofagasta, Chile. *Revista Chilena de Historia Natural* 74: 841–853, https://doi.org/10.4067/S0716-078X2001000400011

Darrigan G, Agudo-Padron I, Baez P, Belz C, Cardoso F, Carranza A, Collado G, Correoso M, Cuezzo MG, Fabres A, Gregoric DEG, Letelier S, Ludwig S, Mansur MC, Pastorino G, Penchaszadeh P, Peralta C, Rebolledo A, Rumi A, Santos S, Thiengo S, Vidigal T, Damborenea C (2020) Non-native mollusks throughout South America: emergent patterns in an understudied continent. *Biological Invasions* 22: 853–871, https://doi.org/10.1007/s10530-019-02178-4

Dumont CP, Harris LG, Gaymer CF (2011) Anthropogenic structures as a spatial refuge from predation for the invasive bryozoan *Bugula neritina*. *Marine Ecology Progress Series* 427: 95–103, https://doi.org/10.3354/meps09040

Dumont CP, Urriago JD, Abarca A, Gaymer CF, Thiel M (2009) The native rock shrimp *Rhynchocinetes* typus as a biological control of fouling in suspended scallop cultures. *Aquaculture* 292: 74–79, https://doi.org/10.1016/j.aquaculture.2009.03.044

Ferreira CEL, Junqueira A de OR, Villlac MC, Lopes RM (2009) Marine bioinvasions in the Brazilian coast: brief report on history of events, vectors, ecology, impacts and management of non-indigenous species. In: Rilov G, Crooks JA (eds), Biological Invasions in Marine Ecosystems. Springer-Verlag, pp 459–477, https://doi.org/10.1007/978-3-540-79236-9_27

Figueroa NL, Brante A (2020) Estado actual del conocimiento de las bioinvasiones marinas en Venezuela: temáticas desarrolladas y tendencia temporal. *Gayana* 84: 1–15, https://doi.org/10.4067/S0717-65382020000100001

Figueroa NN, Brante A, Viard F, Lecler J-C (2021) Greater functional similarity in mobile compared to sessile assemblages colonizing artificial coastal habitats. *Marine Pollution Bulletin* 172, 112844, https://doi.org/10.1016/j.marpolbul.2021.112844

Fowler AE, Blakeslee AMH, Canning-Clode J, Repetto MF, Phillip AM, Carlton JT, Moser FC, Ruiz GM, Miller W (2016) Opening Pandora's bait box: a potent vector for biological invasions of marine species. *Diversity and Distributions* 22: 30–42, https://doi.org/10.1111/ddi.12376

Fuentes N, Marticorena A, Saldana A, Jerez V, Ortiz JC, Victoriano P, Moreno RA, Larrain J, Villasenor-Parada C, Palfner G, Sanchez P, Pauchard A (2020) Multi-taxa inventory of naturalized species in Chile. *NeoBiota* 60: 25–41, https://doi.org/10.3897/neobiota.60.55366

Gorski K, Gonzalez JF, Vivancos A, Habit EM, Ruzzante DE (2017) Young-of-the-year coho salmon *Oncorhynchus kisutch* recruit in fresh waters of remote Patagonian fjords in southern Chile (51oS). *Biological Invasions* 19: 1127–1136, https://doi.org/10.1007/s10530-016-1341-9

Häussermann V (2006) Biodiversity of Chilean sea anemones (Cnidaria: Anthozoa): distribution patterns and zoogeographic implications, including new records for the ford region. *Investigaciones Marinas* 34: 23–35, https://doi.org/10.4067/S0717-71782006000200003

Häussermann V, Försterra G (2005) Distribution patterns of Chilean shallow-water sea anemones (Cnidaria: Anthozoa: Actiniaria, Corallimorpharia); with a discussion of the taxonomic and zoogeographic relationships between the actinofauna of the South East Pacific, the South West Atlantic and the Antarctic. *Scientia Marina* 69: 91–102, https://doi.org/10.3989/scimar.2005.69s291

Häussermann V, Gutstein CS, Beddington M, Cassis D, Olavarria C, Dale AC, Valenzuela-Toro AM, Perez-Alvarez MJ, Sepulveda HH, McConnell KM, Horwitz FE, Forsterra G (2017) Largest baleen whale mass mortality during strong El Nino event is likely related to harmful toxic algal bloom. *PeerJ* 5: e3123, https://doi.org/10.7717/peerj.3123

Häussermann V, Molinet C, Díaz M, Försterra G, Henríquez J, Espinoza K, Matamala T, Hüne M, Cárdenas C, Glon H, Barahona T, Subiabre D (2022). Recent massive invasions of the circumboreal sea anemone *Metridium senile* in North and South Patagonia. *Biological Invasions* 24: 3665–3674, https://doi.org/10.1007/s10530-022-02878-4

Hermoso M, Martin VY, Gelcich S, Stotz W, Thiel M (2021) Exploring diversity and engagement of divers in citizen science: Insights for marine management and conservation. *Marine Policy* 124: 104316, https://doi.org/10.1016/j.marpol.2020.104316

IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio ES, Settele J, Díaz S, Ngo HT (eds), IPBES secretariat, Bonn, Germany, 1148 pp, https://doi.org/10.5281/zenodo.3831673

Jofré-Madariaga DJ, Rivadeneira MM, Tala F, Thiel M (2014) Environmental tolerance of the two invasive species *Ciona intestinalis* and *Codium fragile*: their invasion potential along a temperate coast. *Biological Invasions* 16: 2507–2527, https://doi.org/10.1007/s10530-014-0680-7

Kennish MJ (2015) Anthropogenic impacts. In: Kennish MJ (ed), Encyclopedia of Estuaries. Springer-Verlag, pp 29–35, https://doi.org/10.1007/978-94-017-8801-4_246

Krüger I, Lenz M, Thiel M (2018) The colonial ascidian *Diplosoma listerianum* enhances the occurrences of the hydrozoan *Obelia* sp. during early phases of succession. *Helgoland Marine Research* 72: 4, https://doi.org/10.1186/s10152-018-0506-6

Leclerc J-C, Viard F, Gonzalez-Sepulveda E, Diaz C, Hinojosa JN, Araneda KP, Silva F, Brante A (2020) Habitat type drives the distribution of non-indigenous species in fouling communities regardless of associated maritime traffic. *Diversity and Distributions* 26: 62–75, https://doi.org/10.1111/ddi.12997

Leclerc J-C, Brante A, Viard F (2021) Rapid recovery of native habitat-builders following physical disturbance on pier pilings offsets colonization of cryptogenic and non-indigenous species in a Chilean port. *Marine Environmental Research* 163: 105231, https://doi.org/10.1016/j.marenvres.2020.105231

León-Muñoz J, Urbina MA, Garreaud R, Iriarte JL (2018) Hydroclimatic conditions trigger record harmful algal bloom in western Patagonia (summer 2016). *Scientific Reports* 8: 1330, https://doi.org/10.1038/s41598-018-19461-4

Letelier SV (1999) Introduccion des especies exoticas en America del Sur. *Boletin Amici Molluscarum (Sociedad Malacologia de Chile)* 7: 14–16

Lopes RM (ed), Informe sobre as especies exoticas invasoras marinhas no Brasil. Ministerio do Meio Ambiente. Brasilia: MMA/SBF, 440 pp

Manríquez PH, Fica E, Ortiz V, Castilla JC (2014) Bio-incrustantes marinos en el canal de Chacao, Chile: un estudio sobre potenciales interacciones con estructuras manufacturadas por el hombre. *Revista de Biologia Marina y Oceanografia* 49: 243–265, https://doi.org/10.4067/S0718-19572014000200006

Manríquez PH, Castilla JC, Ortiz V, Jara ME (2016) Empirical evidence for large-scale human impact on intertidal aggregations, larval supply and recruitment of *Pyura praeputialis* around the Bay of Antofagasta, Chile. *Austral Ecology* 41: 701–7014, https://doi.org/10.1111/aec.12359

Meyerson LA, Simberloff D (2020) Special Issue: Early Detection and Rapid Response. *Biological Invasions* 22(1): 1–176

Molinet C, Häussermann V, Astorga M, Barahona N (2023) Population expansion of the invasive sea anemone *Metridium senile* in the spatial mesoscale of a sea urchin bed in north-western Patagonia. *Biological Invasions* 25: 1101–1118, https://doi.org/10.1007/s10530-022-02965-6

Moreno RA, Neill PE, Rozbaczylo (2006) Native and non-indigenous boring polychaetes in Chile: a threat to native and commercial mollusc species. *Revista Chilena de Historia Natural* 79: 263–278, https://doi.org/10.4067/S0716-078X2006000200012

Navarrete SA, Castilla JC (1993) Predation by Norway rats in the intertidal zone of central Chile. *Marine Ecology Progress Series* 92: 187–199, https://doi.org/10.3354/meps092187

Neill PE, Alcalde O, Faugeron S, Navarrete SA, Correa JA (2006) Invasion of *Codium fragile* spp. tomentosoides in northern Chile: a new threat for *Gracilaria* farming. *Aquaculture* 259: 202–210, https://doi.org/10.1016/j.aquaculture.2006.05.009

Neill PE, Rozbaczylo N, Villaseñor-Parada C, Guzmán-Rendón G, Sampértegui S, Hernández CE (2020) Patterns of association of native and exotic boring polychaetes on the southeastern Pacific coast of Chile: the combined importance of negative, positive and random interactions. *PeerJ* 8: e8560, https://doi.org/10.7717/peerj.8560

Nellemann C, Hain S, Alder J (eds), (2008) In Dead Water - Merging of climate change with pollution, over-harvest, and infestations in the world's fishing grounds. United Nations Environment Programme, GRID-Arendal, Norway, 64 pp

Ortiz M, Wolff M (2002) Trophic models of four benthic communities in Tongoy Bay, Chile: comparative analysis and preliminary assessment of management strategies. *Journal of Experimental Marine Biology and Ecology* 268: 205–235, https://doi.org/10.1016/S0022-0981(01)00385-9

Pacheco AS, Andrade DG (2020) Decline of a non-native ecosystem engineer and its replacement with a native on rocky shores: effects on the diversity and structure of benthic communities. *Marine Biodiversity* 50: 2, https://doi.org/10.1007/s12526-019-01033-y

Pacheco CJ, Castilla JC (2000) Ecología trófica de los ostreros *Haematopus palliatus* pitanay (Murphy 1925) y *Haematopus ater* (Vieillot et Oudart 1825) en mantos del tunicado *Pyura praeputialis* (Heller 1878) en la Bahía de Antofagasta, Chile. *Revista Chilena de Historia Natural* 73: 533–541, https://doi.org/10.4067/S0716-078X2000000300017

Perez V (2014) El registro de *Perna perna* (Linne, 1758) (Mollusca: Lamellibranchia) para el estrecho de Magallanes. *Anales Instituto Patagonia* 42: 89–91, https://doi.org/10.4067/S0718-686X2014000200009

Perez JE, Alfonsi C, Salazar SK, Macsotay O, Barrios J, Escarbassiere RM (2007) Especies marinas exoticas y criptogenicas en las costas de Venezuela. *Boletin del Instituto Oceanografico de Venezuela* 46: 79–96

Radashevsky VI, Olivares C (2005) *Polydora uncinata* (Polychaeta: Spionidae) in Chile: an accidental transportation across the Pacific. *Biological Invasions* 7: 489–496, https://doi.org/10.1007/s10530-004-5686-0

Radashevsky VI, Migotto AE (2017) First report of the polychaete *Polydora hoplura* (Annelida: Spionidae) from North and South America and Asian Pacific. *Marine Biodiversity* 47: 859–868, https://doi.org/10.1007/s12526-016-0515-0

Rahel FJ, Bierwagen B, Taniguchi Y (2008) Managing aquatic species of conservation concern in the face of climate change and invasive species. *Conservation Biology* 22: 551–561, https://doi.org/10.1111/j.1523-1739.2008.00953.x

Sandoval M, Parada C, Torres R (2018) Proposal of an integrated system for forecasting harmful algal blooms (HAB) in Chile. *Latin American Journal of Aquatic Research* 46: 424–451, https://doi.org/10.3856/vol46-issue2-fulltext-18

Schwindt E, Carlton JT, Orensanz JM, Scarabino F, Bortolus A (2020) Past and future of the marine bioinvasions along the Southwestern Atlantic. *Aquatic Invasions* 15:11–29, https://doi.org/10.3391/ai.2020.15.1.02

Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pysek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L, Dawson W, Dulinger S, Fuentes N, Jager H, Kartesz J, Kenis M, Kreft H, Kuhn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Stajerova K, Tokarska-Guzik B, van Kleunen M, Walker K, Weigelt P,Yamanaka T, Essl F (2017) No saturation in the accumulation of invasive species worldwide. *Nature Communications* 8: 14435. https://doi.org/10.1038/ncomms14435

Soto D, Jara F, Moreno C (2001) Escaped salmon in the inner seas, southern Chile: facing ecological and social conflicts. *Ecological Applications* 11: 1750–1762, https://doi.org/10.1890/1051-0761(2001)011[1750:ESITIS]2.0.CO;2

Soto D, Arismendi I, Olivos JA, Canales-Aguirre CB, Leon-Muñoz J, Niklitschek EJ, Sepúlveda M, Paredes F, Gomez-Uchida D, Soria-Galvarro Y (2023) Environmental risk assessment of non-native salmonid escapes from net pens in the Chilean Patagonia. *Reviews in Aquaculture* 2022: 1–22, https://doi.org/10.1111/raq.12711

Uribe E, Etchepare I (2002) Effects of biofouling by *Ciona intestinalis* on suspended culture of *Argopecten purpuratus* in Bahia Inglesa, Chile. *Bulletin of the Aquaculture Association of Canada* 102: 93–95

Valdivia N, Heidemann A, Thiel M, Molis M, Wahl M (2005) Effects of disturbance on the diversity of hard-bottom macrobenthic communities on the coast of Chile. *Marine Ecology Progress Series* 299: 45–54, https://doi.org/10.3354/meps299045

Villasenor-Parada C, Ramirez ME, Macaya EC (2018) Macroalgas exóticas en la costa de Chile: patrones espaciales y temporales en el proceso de invasión. *Latin American Journal of Aquatic Research* 46: 147–165, https://doi.org/10.3856/vol46-issue1-fulltext-15

Williams SL, Davidson IC, Pasari JR, Ashton GV, Carlton JTC, Crafton RE, Fontana RE, Grosholz ED, Miller W, Ruiz GM, Zabin CJ (2013) Managing multiple vectors for marine invasions in an increasingly connected world. *Bioscience* 63: 952–966, https://doi.org/10.1525/bio.2013.63.12.8

Websites, online documents and databases

Armada de Chile (2021) Boletín Estadístico Marino – Edición 2021. Ministerio de Defensa de Chile, https://www.directemar.cl/directemar/site/docs/20210630/20210630150737/baja_boletin_estadistico_2021.pdf (accessed 12 September 2023)

CEEI (2018) Comité de Especies Exóticas Invasoras. Protocolo de Respuesta ante Especies Exóticas Invasoras. Uruguay https://www.gub.uy/sistema-nacional-emergencias/comunicacion/publicaciones/protocolo-respuesta-ante-invasiones-biologicas-especies-exoticas (12 sept 2023)

CITES (2004) Convention on International Trade in Endangered Species of Wild Fauna and Flora. Trade in alien invasive species. Resolution Conf.13.10 (Rev.CoP14). https://cites.org/eng/res/13/13-10R14.php

Comité Asesor Nacional sobre Especies Invasoras (2010) Estrategia nacional sobre especies invasoras en México, prevención, control y erradicación. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Comisión Nacional de Áreas Protegidas, Secretaría de Medio Ambiente y Recursos Naturales. México 94 pp. http://www.conabio.gob.mx/institucion/Doc/Estrategia_Invasoras_Mex.pdf

Comité Operativo para el Control de las Especies Exóticas Invasoras (2014) Estrategia Nacional Integrada para la Prevención, el Control y/o Erradicación de las Especies Exóticas Invasoras. Ministerio del Medio Ambiente. Santiago, 26 pp. https://especies-exoticas.mma.gob.cl/wp-content/uploads/2018/12/A.2.-Estrategia-EEI-digital.pdf

DIRECTEMAR (2012) ORDINARIO/PERMANENTE CIRCULAR A-51/002–2012. Dirección General del Territorio Marítimo y de Marina Mercante, Ministerio de Defensa Nacional | Gobierno de Chile, Santiago, Chile https://www.directemar.cl/directemar/site/docs/20170301/20170301165316/a51_002.pdf (accessed 12 September 2023)

DIRECTEMAR (2018) ORDINARIO/PERMANENTE CIRCULAR A-52/007–2018. Dirección General del Territorio Marítimo y de Marina Mercante, Ministerio de Defensa Nacional | Gobierno de Chile, Santiago, Chile https://www.directemar.cl/directemar/site/docs/20190305/20190305154321/a_52_007_06_12_18.pdf (accessed 12 September 2023)

EF-EPI (2021) Education First – English Proficiency Index. https://www.ef.com/cl/epi/ (accessed 12 September 2023)

Fondo de Inversión Ambiental Sostenible (2018) Plan de Manejo de Especies Invasoras para Galápagos (2019–2029) https://unidosporgalapagos.files.wordpress.com/2021/05/5.-plan-especies-invasoras-gps.pdf (accessed 12 September 2023)

Lloyd's Register (2019) National Ballast Water Management Requirements. London, 46 pp. https://britanniapandi.com/wp-content/uploads/2019/07/LR_National-ballast-water-management-requirements-03-2019.pdf (accessed 12 September 2023)

Ministerio del Ambiente (2019) Plan de acción decenal para la prevención, manejo y control de las especies exóticas en Ecuador continental. (A. Vela, A. Factos, J. Olmedo, & V. Chocho (eds.)). Zenodo. https://doi.org/10.5281/zenodo.3581243

Ministerio del Medio Ambiente (2023), Ley 21600. Crea El Servicio De Biodiversidad y Áreas Protegidas y el Sistema Nacional de Áreas Protegidas. https://www.bcn.cl/leychile/navegar?idNorma=1195666&idVersion=2023-09-06 (accessed 12 September 2023)

Ministério do Meio Ambiente (2018) Comissão Nacional de Biodiversidade. Resolução Nº 7, de 29 de Maio De 2018, https://antigo.mma.gov.br/biodiversidade/comissao-nacional-de-biodiversidade/resolucoes (accessed 12 September 2023)

SUBPESCA (2022) Res. Ex. Nº 2266-2022 Fija Nómina de Especies Hidrobiológicas Vivas de Importación Autorizada. Deja sin Efecto Resolución que Señala. https://www.subpesca.cl/portal/615/w3-article-116303.html (F.D.O. 11-11-2022)

Supplementary material

The following supplementary material is available for this article:

Appendix 1. Workshop agenda
Appendix 2: First Survey - Past, Present and Future of marine bio-invasions in Chile
Appendix 3: Second Survey
Appendix 4: Results of Survey 1
Appendix 5: Results of Survey 2
Appendix 6: Working Group Discussion Results

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