

Editorial**Current research, pressing issues, and lingering questions in marine invasion science: lessons from the Tenth International Conference on Marine Bioinvasions (ICMB-X)**Amy E. Fowler^{1*}, April M.H. Blakeslee², Alejandro Bortolus³, Joana Dias⁴, Carolyn K. Tepolt⁵ and Evangelina Schwindt⁶¹Department of Environmental Science and Policy, George Mason University, Fairfax, VA, USA²Biology Department, East Carolina University, E 10th Street, Greenville, NC, USA³Grupo de Ecología en Ambientes Costeros (GEAC), IPEEC-CONICET, Puerto Madryn, Argentina⁴NOAA Northwest Fisheries Science Center, Seattle, WA, USA⁵Department of Biology, Woods Hole Oceanographic Institution, Woods Hole, MA, USA⁶Grupo de Ecología en Ambientes Costeros (GEAC), IBIOMAR-CONICET, Puerto Madryn, Argentina

*Corresponding author

Author e-mails: afowler6@gmu.edu (AEF), blakesleeap14@ecu.edu (AMHB), bortolus@gmail.com (AB), jdias@uw.edu (JD), ctepolt@whoi.edu (CKT), schwindt@whoi.edu (ES)**Co-Editors' Note:** This study was first presented at the 10th International Conference on Marine Bioinvasions held in Puerto Madryn, Argentina, October 16–18, 2018 (<http://www.marinebioinvasions.info>). Since their inception in 1999, the ICMB meetings have provided a venue for the exchange of information on various aspects of biological invasions in marine ecosystems, including ecological research, education, management and policies tackling marine bioinvasions.**Citation:** Fowler AE, Blakeslee AMH, Bortolus A, Dias J, Tepolt CK, Schwindt E (2020) Current research, pressing issues, and lingering questions in marine invasion science: lessons from the Tenth International Conference on Marine Bioinvasions (ICMB-X). *Aquatic Invasions* 15(1): 1–10, <https://doi.org/10.3391/ai.2020.15.1.01>**Received:** 17 January 2020**Accepted:** 12 March 2020**Published:** 21 March 2020**Handling editor:** Vadim Panov**Copyright:** © Fowler et al.

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OPEN ACCESS**Introduction**

Research on marine bioinvasions is an inherently international collaboration. Species range boundaries have become more fluid in recent decades as a result of enhanced human globalization, leading to species translocations across international boundaries through high profile vectors (e.g., shipping, hull fouling, aquaculture, etc.) (Ruiz et al. 2000; Seebens et al. 2013). Global trade and anthropogenic activities that promote invasive species spread continue to increase, rising by an average of 70% since 1970, with no sign of saturation (Pagad et al. 2015; Seebens et al. 2017). Even though these numbers are primarily based on terrestrial systems, recent work has demonstrated that marine ecosystems are as severely impacted by invasive species as by other human activities including overfishing, pollution (including plastics), climate change, and ocean acidification (Diaz et al. 2019). Species introductions to seas, coasts, and estuaries are therefore a global threat to human and non-human populations alike. As such, scientists and managers are increasingly focused on prevention and management, risk analysis and prioritization, and innovative technologies to detect novel species.

Urgent transformative changes in policy are needed to prevent further deterioration of natural ecosystems at the global scale. As invasive species are one of the greatest concerns, the Convention on Biological Diversity wrote a Strategic Plan on Biodiversity for 2011–2020 that included a specific Aichi Biodiversity Target on invasive species. This biodiversity target (#9 under Strategic Goal B: Reduce the direct pressures on biodiversity and

promote sustainable use) says “By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment.” However, the progress made by nations worldwide to achieve this target has been poor (Diaz et al. 2019). As a result, two international initiatives were recently launched to produce a global assessment of invasive species. The first is led by the United Nations General Assembly, which is undertaking a new Assessment of the State of the Marine Environment, including socioeconomic aspects. This assessment (delivery expected December 2020) includes, for the first time, a chapter dedicated to marine invasive species (Evans et al. 2019). The second is the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, started in 2019 and expected to finish by 2023), which includes a thematic assessment of invasive species and their control. This assessment will analyze trends, direct and indirect drivers, impacts, and the effectiveness of past and current management programs and tools and will explore future options for the prevention and management of marine biological invasions. These two initiatives are vital steps toward evaluating the threat caused by invasive species to marine biodiversity, ecosystem services, livelihoods and the search for urgent solutions. It is therefore imperative for conferences like the International Conference on Marine Bioinvasions (ICMB) to serve as a venue to bring international researchers together to discuss current research and management strategies. The ICMB is truly an international conference, with the last four meetings held on different continents, and the group is committed to supporting travel for international researchers from many countries to attend its meetings. These conferences are not only integral to sharing and discussing research and establishing collaborations, but they also highlight the continued need for additional research to fill gaps in our understanding.

ICMB-X Conference and Content of the Special Issue

The Tenth ICMB (ICMB-X; <http://www.marinebioinvasions.info>) was held October 16–19, 2018 in Puerto Madryn, Argentina, marking the first time the conference was hosted in Latin America in its 20-year history (Bortolus and Schwindt 2018). ICMB-X brought together a geographically- and gender-balanced team of seven leading keynote speakers who joined students, academics, environmental managers and industry leaders from over 40 countries to highlight current challenges in global management and share progress and new initiatives in research, science and policy. During the conference, the Steering Committee presented 15 travel awards: five Judith A. Pederson and James T. Carlton Early Career Scientists Awards, five awards from the Society for the Study of Marine Bioinvasions, Inc. (for international applicants), and five awards from the Office of Naval Research – Global (for Latin American applicants). ICMB-X themes included international networks,

citizen science, biofouling and regional spread, the ecological consequences of climate change for bioinvasions, and risk assessment and management strategies, organized into 11 oral sessions and one poster session. These included the following four targeted special sessions on emerging research topics: (1) Functional ecology of marine bioinvasions, (2) Development and application of eDNA and RNA tools for improved marine biosecurity surveillance, (3) Adaptive evolution in biological invasions, and (4) Natural factors and management actions that regulate outbursts of populations. All told, ICMB-X featured 191 research presentations and was attended by 150 participants from 25 countries and every continent except Antarctica (Figure 1; <http://www.marinebioinvasions.info/abstract-book>). One of the greatest accomplishments of this conference was highlighting novel research conducted throughout South America. These accomplishments included the presentation of the first book devoted to marine coastal invasive species of Argentina (Schwindt et al. 2018), a country which has historically lacked emphasis on research in marine bioinvasions even as the government supports the introduction of commercial species known to be invasive (Schwindt and Bortolus 2017).

Research from all of the sessions was represented by 11 papers recently published in a special issue of *Aquatic Invasions* (Blakeslee et al. 2020; Castro et al. 2020; Guilhem et al. 2020; Keanly and Robinson 2020; Lins and Rocha 2020; Ojaveer et al. 2020; Oricchio and Dias 2020; Ramos-Esplá et al. 2020; Schwindt et al. 2020; Teixeira and Creed 2020; and Yorio et al. 2020) as well as two additional papers in a special issue of *Management of Biological Invasions* (Couton et al. 2019; Cunningham et al. 2019; <https://www.reabic.net/journals/mbi/2019/Issue4.aspx>). Below, the 11 papers in the special issue of *Aquatic Invasions* are explored in the context of the major themes of ICMB-X.

International and national networks to monitor and describe species invasions

As invasive species do not recognize international borders, it is imperative that scientists work together across boundaries to share information and document species introductions. Within that framework, Schwindt et al. (2020) coordinated a group of scientists from Argentina, Uruguay, and the United States to review and update all the marine invasions in the southern Southwest Atlantic Ocean. They added 100 new introduced and 43 new cryptogenic species to a previously published list for a total of 129 introduced and 72 cryptogenic marine species. In another examination of marine invasions in South America, Teixeira and Creed (2020) investigated the 8000 km coastline of Brazil, describing a total of 138 marine non-indigenous species in Brazilian waters, with the highest richness in states with the greatest shipping (calculated as proportion of total tonnage of Brazilian maritime imports and exports per state). Schwindt et al. (2020)



Figure 1. The Tenth International Conference on Marine Bioinvasions held October 16–19, 2018 in Puerto Madryn, Patagonia Argentina, marking the first time ICMB had been hosted by a Latin American country. Above: Group photo of attendees (Photo: Nicolás Battini). Below: Conference field trip to the Cerro Avanzado Patagonian Rocky Marsh (Photo: Ale Bortolus).

and Teixeira and Creed (2020) both proposed that the majority of these introductions were due to shipping vectors and highlighted the importance of ongoing efforts to manage ballast water and hull fouling in South American waters. Additionally, both research groups emphasized the importance of long-term monitoring programs to efficiently survey these understudied regions for new invaders and to track changes in the abundance and distribution of species already present.

Shipping Vectors: Biofouling and Ballast

As increasingly efficient and widespread global trade and shipping pathways are a major vector for species introductions, a second persistent theme of ICMB is the role of biofouling and ballast water in spreading organisms and the importance of establishing management mechanisms to stop their spread. Shipping and hull fouling introductions are still a global problem; new methods and solutions for combating the issue continue to be a high priority for many managers and governments, and this area of research remains highly productive. Biofouling in particular has been increasingly recognized as an important vector for marine bioinvasions and was the focus of several ICMB-X presentations. One such biofouling species is the compound ascidian genus *Symplegma*; Ramos-Espla et al. (2020) recently morphologically confirmed an invasive species of *Symplegma* (*S. brakenhielmi*, a colonial species) in the Mediterranean Sea. Based on color morphs and locations of spread (i.e., ports), the authors suggested that the species is currently being transported via shipping to new locations around the Mediterranean coast. Two other *Symplegma* species are noted invaders in the Mediterranean Sea (*S. rubra*, *S. reptans*), but *S. brakenhielmi* has spread more quickly, possibly due to its rapid, colonial growth form and viviparous reproductive mode (other species are solitary and ovoviviparous).

In addition to transoceanic shipping, recreational vessels can be important secondary vectors for the spread of invasive species, making them a promising target for management efforts (Wasson et al. 2001; Lacoursière-Roussel et al. 2016). Castro et al. (2020) showed that beaching and manually cleaning small and medium sized vessels on a tarp (to collect dislodged organisms) during a low tide sequence could effectively remove 12.5 m³ of hull fouling. While the authors acknowledge that this method cannot be used in all cases, it is a recommended alternative when local regulations do not allow for in-water cleaning or when dry-docking is not available. In another investigation, Keanly and Robinson (2020) conducted a series of laboratory and field trials to remove biofouling from recreational vessels via encapsulation (i.e., wrapping the hull in plastic). While all biota died within three days during the laboratory study, it took between three and four days for complete mortality of fouling organisms in the field. The authors suggest that this method of hull cleaning should be further tested for application in adaptive management.

Species Interactions and Invasion Ecology

Bioinvasion ecology, or the interactions of introduced organisms with novel environments and communities, is a third central theme of ICMB. Ecology has been always a core focus of invasion biology. Biological invasions have long been recognized as natural experiments with which to explore the structure and function of ecological communities (Elton 1958; Blackburn 2008), and to improve the way we perceive the fragility of ecosystems and landscapes deeply associated with our culture and history (Bortolus et al. 2015). In the paper by Guilhem et al. (2020), the ability of a Brazilian native zoantharian (Anthozoan *Palythoa caribaeorum*) to grow when in competition for space depended on which invasive species of sun coral (*Tubastraea tagusensis*, *T. coccinea*) it was competing against. While both invasive corals affected the native species, *T. coccinea* had more negative effects (i.e., discoloring, increased distance from competitor, and decreased growth rates) on the native species. The authors were able to show that native zoantharian exhibited biotic resistance to *T. tagusensis* (and one colony actually overgrew *T. tagusensis*), but the relative roles of the potential mechanisms (i.e., physical or chemical, or both) remain unknown. Lins and Rocha (2020) also explored the impacts of invasive fouling species on the growth of native species. In their survey in Brazil, commercially important mussels (*Perna perna*) were 19–36% smaller in size and weighed 60% less when they were fouled by invasive species (the ascidian *Didemnum perlucidum*, barnacle *Megabalanus coccopoma*, and/or bryozoan *Schizoporella errata*). Based on the species with the most negative impacts to *P. perna* dry and wet weights, Lins and Rocha (2020) suggested that invasive species management for this commercial fishery should focus on combating *D. perlucidum* and *M. coccopoma*.

With new species being introduced frequently, novel pairings and species interactions will continue to be a source of new science in bioinvasions research, and more broadly in fields including ecophysiology, community ecology, and evolutionary biology. Invasive fouling species can also interact with one another, and the strength and outcomes of those interactions fluctuate seasonally and depend on predation pressure. In their field experiment, Oricchio and Dias (2020) exposed colonies of *D. perlucidum*, *S. errata*, and the cryptogenic ascidian *Botrylloides niger* to fully crossed competition (no competition, interspecific competition, or intraspecific competition) and predation (protected or exposed) treatments in Brazil for four weeks. The growth of the two ascidian species accelerated under low predation pressure and during the summer, while the growth of the mineralized *S. errata* was only impacted seasonally (i.e., its highest growth rate was in summer) and it had high survival rates even under high predation pressure. Overall, the authors found that predation was an important biotic driver of community composition, but in the absence of predation,

interspecific competition played a role in species' growth rates. While invasive species have detrimental impacts on natives, their roles in their new ecological communities may not be entirely negative (e.g., Schwindt et al. 2001). Yorio et al. (2020) explored the importance of the introduced green crab (*Carcinus maenas*) in the diet of the native kelp gull (*Larus dominicanus*) in Argentina. The authors investigated gulls at several points in their breeding cycle at five sites over two years and determined that while green crabs were not a major component of gull diets, they were consumed regularly and likely supplemented the birds' diets during reproduction in areas where crabs had been established for the longest amount of time (Yorio et al. 2020). Studies like these, which explore the impacts of invasive species on native species, remain a cornerstone of bioinvasions ecological research.

Host-Parasite Interactions in Invasions

Parasites are an often over-looked group of marine taxa with vital ecological roles. These roles can be shifted or re-aligned (or lost) post-invasion and provide a platform for novel ecological and evolutionary research. Parasites can be invasive themselves (i.e., transferred with an invasive host or as a free-living stage), or native parasites may host-switch to take advantage of a novel invasive host. For example, Ojaveer et al. (2020) found that 78% of invasive round gobies (*Neogobius melanostomus*) in the northeast Baltic Sea were parasitized, with their parasitofauna comprising a total of 24 native parasites from five different taxonomic groups. The probability of being infected by one of these parasites was greatest in larger, female fish caught in the autumn. This study also highlighted the role of invasive species in promoting parasite spillback. Parasite spillback occurs when an invasive species becomes an additional or alternative host for native parasites, allowing native parasites to increase in prevalence and intensity with potential impacts on higher trophic level organisms that serve as definitive hosts. In another host-parasite investigation, Blakeslee et al. (2020) examined the role of host-parasite coevolutionary history on host susceptibility in native (Europe) and invasive (North America) populations of the European green crab, *Carcinus maenas*. Using a crossed experimental design of hosts and trematode parasites from the crab's two ranges, the authors found that European hosts exposed to European parasites (i.e., long-term coevolutionary history) had the lowest infection prevalence and abundance, while European crabs exposed to North American parasites (i.e., no coevolutionary history) had the highest abundance of infection. North American crabs exposed to North American parasites (i.e., ~ 200 year coevolutionary history) exhibited a median level of infection as compared to the other groups, highlighting the importance of time-since-introduction in determining the susceptibility of novel hosts to native parasites.

Conclusions

The Tenth International Conference on Marine Bioinvasions (ICMB-X), chaired by Dr. Evan Schwindt and Dr. Ale Bortolus, was an excellent platform on which to exchange scientific ideas, reconnect with old friends and colleagues, forge new collaborations, and enjoy the local Argentinian culture and hospitality. The ICMB-X would not have been possible without the tireless efforts of the Grupo de Ecología en Ambientes Costeros (<https://geaccenpat.wixsite.com/geac>). With the ICMB-X concluded and the next ICMB planned for 2021 in Annapolis, MD, USA (hosted by Dr. Greg Ruiz and the Smithsonian Environmental Research Center), we must look ahead and continue advancing the field of marine bioinvasions research. One emerging research focus has been the drifting of anthropogenic debris as a novel vector for marine species not only along coastlines, but also across oceans. A recent Special Issue in *Aquatic Invasions* (March 2018, Volume 13) highlighted this phenomenon after the earthquake and subsequent tsunami off the coast of Tōhoku, Japan in 2011. Anthropogenic climate change and its impacts (i.e., range expansions, warming seas, sea level rise, and increased storms) also play a role in vector ecology and novel species interactions. However, even as species are transported globally, the ability to track and effectively combat their movements is hindered by funding cuts for monitoring programs and research endeavors, denial of the concept of invasive species, and a lack of skilled taxonomists who can discern invaders from native species (Carlton and Fowler 2018). Each of these roadblocks undermines our ability to track how marine communities respond to invasive species and ultimately impairs our ability as researchers and managers to respond to the larger socio-economic (i.e., economic, social, health, and political) impacts of species introductions. One solution is to expand the research scope of invasion ecology and place bioinvasion research (i.e., biosecurity) at the forefront of major conservation issues threatening our coastlines and seas. This can help ensure continued funding and the future sustainability of the discipline. In a world deeply concerned by the spread of pandemic infectious organisms, our capacity to understand the ecology and evolution of invasive species, their spread routes and colonization strategies, and how to prevent and manage their spread is more critical than ever to creating sound interdisciplinary protocols that will assist decision-makers and international organizations. In parallel with these goals, continued and novel collaborations among international scientists and agencies is of utmost importance and should continue to be a focal point of growth in the field.

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