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Editorial

ICAIS advances knowledge and understanding of aquatic invasions in the Anthropocene

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The latest International Conference on Aquatic Invasive Species (ICAIS; http://www.ICAIS.org) was held in the city of Montreal, Canada between October 27 and October 31, 2019. Under the theme "Aquatic Invasions in the Anthropocene" ICAIS 2019 presented some of the best science on invasive species in marine and freshwater environments to the benefit of scientists, students, managers and stakeholders around the world. It also emphasized emerging and novel research in invasion ecology and its applications, including seven keynote presentations from a diverse group of international scientific leaders, 121 concurrent session oral presentations, and 49 poster presentations.

As in past conferences, ICAIS 2019 explored topics such as impacts on biodiversity and ecosystems, new developments in the management and control of invasive species, policies and public awareness, and emerging vectors, invasion pathways and threats. Keynote talks by renowned researchers reflected the different sessions and included topics as varied as the importance of biogeography in the origins of invasion sciences (Anthony Ricciardi – Canada), successes and failures in the management of invasions on land (David Simberloff – USA), the multiple environmental stressors that shape community response to non-native species (Shelley Arnott – Canada); the many ways in which humans assist biological invaders after their arrival (Emma Johnston – Australia), the impacts of species invasions in a changing world (Cascade Sorte – USA), and the colonization pressure and the insights of supply-side invasion ecology (Julie Lockwood – USA).

For the first time in more than twenty years, ICAIS added a special session called "Integrating Invasion Science and Management Across Realms: Learning from Terrestrial, Marine, and Freshwater Experiences". Seven guest speakers participated in this session addressing management challenges at different stages of the invasion cycle (risk assessment, vectors, eradication and control). This was followed by an interactive discussion between scientists and managers working on different taxa, communities, and systems, which explored the potential for collaboration to improve results across boundaries of terrestrial and aquatic habitats.

Over the past two decades, ICAIS has become an unmissable forum for scientists, managers and particularly for young researchers and students from all over the world. ICAIS 2019 involved the largest youth contingent in the history of the conference series, with 40 students and 24 early career researchers from 15 countries. Programs designed for this demographic included a student social, career advice workshop, a mentoring lunch, and an oral and poster presentation awards session for the top three in each category.

ICAIS has also kept a record of the conferences held over the last ten years in special issues of the journals *Aquatic Invasions* and *Management of Biological Invasions*. Twelve research articles are published in the ICAIS 2019 special issue of *Management of Biological Invasions* (see Johansson et al. 2021; Adolfsen et al. 2021; Barbour et al. 2021; Bradbeer et al. 2021; Campbell et al. 2021; Collas et al. 2021; Lemmers et al. 2021; Mohit et al. 2021; Oliver et al. 2021; Sesin et al. 2021; Van Poorten and Beck 2021; Verbrugge et al. 2021; Wang and Corbett 2021). This special issue of Aquatic Invasions includes seven articles presented at the ICAIS and three additional contributed papers. These papers cover diverse invasive species issues studied in different habitats worldwide.

Bellini and Becker (2021) studied how anthropogenic alteration of landscapes (i.e., land conversion, pollution or species introduction) is associated with forest clearing of riparian areas which are subsequently highly prone to the establishment of non-native species. The authors investigated several factors associated with the occurrence of *Hedychium coronarium* in the riparian areas of six streams in southern Brazil. *H. coronarium* (white ginger lily) is one of the most common invasive plants in Brazilian wetlands and riparian areas. Originally from the Himalayan region, it usually occupies shaded or semi-shaded areas, with intermediate shading optimal for its growth and reproduction. Considered a very invasive weed (Lim 2014), the white ginger lily has been recorded in 45 countries around the world (GBIF.org). It outcompetes local flora, and has been demonstrated to change the composition of aquatic macroinvertebrate assemblages (Saulino and Trivinho-Strixino 2017). The authors questioned why *H. coronarium* does not occur continuously in riparian environments, in spite of the species being regionally present for a long time. Their study aimed at assessing which dispersal and disturbance drivers, whether natural or anthropic, could determine the presence of *H. coronarium* in riparian areas. Bellini and Becker (2021) hypothesized that local variation in flood intensity along streams could particularly affect the occurrence of *H. coronarium*, with anthropogenic disturbance, and hydrochoric and terrestrial dispersal potentially also favouring the presence of the white ginger lily in riparian areas.

Gettys and Leon (2021) describe their research on the submerged Hydrilla (*Hydrilla verticillata*) a monocotyledonous perennial in the family Hydrocharitaceae referred to as “the perfect aquatic weed”. This cosmopolitan species, which is native to Asia, Central Africa, and Australia, is considered an invader of many aquatic ecosystems worldwide. Hydrilla was first introduced to Florida in the 1950s by aquarium plant growers, escaped cultivation, and had become established in the primary water bodies of all drainage basins in the state by 1970 and was present in over 20,000 ha of Florida’s waters by 1980 (Schardt and Nall 1988). Gettys and Leon (2021) showed how applied management strategies could have different outcomes either because species can develop resistance to herbicides or because eradication or containment programs are not consistent through time. The vast majority of species that evolve resistance to herbicides do so through the genetic mutations that occur during sexual reproduction. Asexually-reproducing Hydrilla would instead have to rely on somatic mutations to become resistant to fluoridone, a herbicide commonly used to control Hydrilla (Netherland and Jones 2015). Gettys and Leon (2021) used the Hardy-Weinberg principle of constant allele frequencies (i.e., $p + q = 1$), to predict allelic frequency shifts within Hydrilla populations due to selection. Although this model is based on a number of assumptions that are violated by species that reproduce asexually, they addressed the assumptions of the model in the context of Hydrilla and compared theoretical model predictions to the likely timeline of actual events that occurred in many bodies of water across Florida. Their study illustrates how the Hardy-Weinberg principle of constant allele frequencies can be used as an exploratory tool to model resistance evolution in asexually reproducing species such as Hydrilla.

Suescún et al. (2021) presented a study on the benthic diatom *Didymosphenia geminata* at ICAIS 2019. This benthic diatom constitutes a major global threat to freshwater ecosystems (Blanco and Ector 2009; Kilroy and Unwin 2011; Reid et al. 2012). Despite two decades of research, the cause of mat proliferations remains uncertain, although bacterial biofilm composition may contribute to successful attachment and consequently proliferation. Suescun et al. (2021) implemented a genomic tool to study the ecological patterns of microorganisms’ associations in biological invasions of *D. geminata* in three aquatic ecosystems of the Chilean Patagonia. Using a metabarcoding approach, the authors identified a core microbiota represented by 4 phyla, 16 families, and 20 genera. *Proteobacteria* (*Alpha* and *Beta*) and *Bacteroidetes* were the dominant phyla, followed by *Cyanobacteria* and *Planctomycetes*. At the lower taxonomic level, unidentified genera from the *Comamonadacea* family were the most abundant bacteria of the core microbiota. This finding was a similar bacterial composition with some relative abundance changes, compared to previous study that reported the bacterial diversity of biofilms from rivers contaminated with *D. geminata* in New Zealand (Brandes et al. 2016). This geographical co-occurrence pattern between bacteria and *D. geminata* in different independent studies suggest that a specific microbiota may be associated with *D. geminata* distributions, establishment and proliferation. Thus, this paper serves as starting point to design an experimental study to determine whether these specific bacteria facilitate the microalgae establishment by creating favorable conditions or are the result of the diatom invasion.

Cárdenas-Calle et al. (2021) studied how numerous marine coastal habitats and species are in danger due to bioinvasions of the invasive octocoral *Carijoa riisei* in highly biodiverse marine benthic ecosystems. With the aims of using molecular techniques to confirm the identification of *C. riisei*, estimating its distribution and abundance, and updating the list of colonized sites, they performed a literature review and studied the distribution at 29 sites along the Ecuadorian coast in 2015. *Carijoa riisei* was recorded in three provinces located in the central and northern coast of Ecuador (Keith and Martínez 2017; Cárdenas-Calle et al. 2018a, b). The areas with highest relative abundance were found in the Manabí, at two sites in Jama: Bajo Londres (44.57%) and Vaca Brava 1 (20.25%). High abundances of *C. riisei* colonies were reported growing over corals and sessile communities in 12% of the sampling sites. Species such as *Pinctada mazatlanica*, *Hyotissa solida*, *Megabalanus peninsularis*, *Muricea plantiginea* and *Aplysina* sp., were observed to be negatively affected by the invasion of *C. riisei*. New records from 2017 showed that the octocoral was found as an epibiont on gas platforms offshore in the El Oro province in the south coast. Cárdenas-Calle et al. (2021) also aimed to identify environmental characteristics associated with the presence of *C. riisei*. Their paper showed that *C. riisei* has established in Ecuador's coasts and tolerates a wide range of habitats and environmental conditions. Data presented in this issue serves as a reference for future monitoring of *C. rissei* in order to estimate the expansion of this species in new areas, develop mitigation programs and take action to conserve marine ecosystems affected by this invasion.

The association between sponges and ophiuroids includes the hosting of the nonindigenous ophiuroid species *Ophiothela mirabilis* Verrill, 1867. Despite being recorded in the Western Atlantic since 2000 (Hendler et al. 2012; Hendler and Brugneaux 2013; Mantelatto et al. 2016), quantitative data is still lacking. To fill this gap of data, Fortunato and Lobo-Hajdu (2021) have quantified the abundance of *O. mirabilis* on marine sponges along the Brazilian coast, and evaluated the relationship of the nonindigenous species with sponge phenotypes. Epibiosis of *O. mirabilis* on sponges was searched in 27 sites from Maranhão to Rio de Janeiro States, Brazil. All interactions were photographed, and the abundance of sponges hosting ophiuroids and abundance of ophiuroids on each sponge individual were counted. Only Bahia and Rio de Janeiro States presented this association, with a positive correlation ($R^2 = 0.71$, $F = 88.33$, $p < 0.001$) between sponge abundance and ophiuroid abundance. Although statistical tests did not show any significant difference for sponges' external morphology, the null probabilistic model suggested *Aplysina fulva* (Pallas, 1766), *Mycale* (*Aegogropila*) *americana* van Soest, 1984 and *Mycale* (*Zygomycale*) *angulosa* (Duchassaing & Michelotti, 1864) may be the preferred hosts for *O. mirabilis*. Absence of host preference and asexual reproduction strategy indicates this species may become an invader along the Western Atlantic Ocean. Therefore, monitoring programs at marine hotspot areas are strongly recommended to avoid potential ecological threats such as alteration of food webs, loss of biodiversity, or changes in coral reef appearance.

Both the quagga mussel (*Dreissena bugensis*) and the zebra mussel (*Dreissena polymorpha*) are notorious for dominating hard substrates in freshwater ecosystems throughout most of the Northern Hemisphere (Therriault et al. 2005; Molloy et al. 2007; Van der Velde et al. 2010; Sousa et al. 2011). Four papers in this issue examined aspects of the dreissenid invasion. Hallidayschult et al. (2021) examined salinity, water clarity, and algal abundance at six sites in the subtropical Lake Texoma, Oklahoma and compared with zebra mussel veliger and post-veliger abundances to understand propagule pressure and establishment. D'Hont et al. (2021) tested the role of movement behaviour differences between zebra and quagga mussels on the ongoing dominance shift between the two species (favoring quagga mussels). Woodruff et al. (2021) modelled the possible impacts of introducing dreissenid mussels into Schuswap Lake, British Columbia, Canada, and Marshall and Stepien (2021) analyzed spatiotemporal population genetic structure of *D. bugensis* and *D. polymorpha* in Lake Erie and the Hudson River between 1994 and 2016.

Zebra mussels have continued to expand their range across North America since their introduction to the Laurentian Great Lakes in the early 1980s. As part of that spread, they necessarily invade water bodies that challenge their environmental tolerances. Hallidayschult et al. (2021) tested how environmental variation affected zebra mussel propagule pressure and establishment in a large, subtropical lake (Lake Texoma, OK-TX). Densities of both veligers in the water column and post-veligers on hard surfaces were significantly higher at sites with higher water clarity, lower salinity, and lower productivity. Also, higher numbers of post-veligers were found on the undersides of deeper surfaces, indicating a potential preference for lower temperatures and refuge from predation. These results highlight the importance of considering environmental heterogeneity within water bodies at the edge of zebra mussels' environmental tolerance when predicting the invasive range and impact of this ecologically and economically disruptive invader.

Despite widespread observations of a dominance shift favouring *D. bugensis,* where both Ponto-Caspian dreissenids co-occur, mechanisms driving this shift are still largely unknown. D' Hont et al. (2021) assessed whether movement behaviour differs between these two mussel species and whether mobility might be a contributing driver to the observed dominance shift. Detachment and mobility of sessile mussel species are supposed to be an avoidance mechanism during unfavourable environmental conditions. The mobility of dreissenids was assessed by tracking movement and location of the dreissenids using time-lapse photography. The experiments mimicked unfavourable habitat conditions by drying, cleaning, tagging and placing mussels in a new environment. After these disturbances, the movement rate, duration, distance, pattern and speed of 299 individuals were monitored. For both species, most individuals moved in more or less circular patterns, causing their actual movement distance to be twice as high as their displacement distance. The average movement duration within 24 hours after the start of each experiment was 65 min, with an average speed of 28 cm/h and average distance of 29 cm. A higher top speed was observed for *D. bugensis* (90 cm/h) than for *D. polymorpha* (60 cm/h). These results support the hypothesis that *D. bugensis* has a competitive advantage over *D. polymorpha* by having a higher top speed and a significantly higher number of individuals moving after a disturbance of their population. Therefore, mobility might be one of the contributing drivers of the observed dominance shift between the species.

New introductions of dreissenid mussels continue to exert bottom-up impacts on freshwater ecosystems across North America. Although they have not yet been invaded, lakes in British Columbia, Canada are at high risk of successful invasion, due to the high level of overland movement of recreational boats and favorable water chemistry and temperature. Woodruff et al. (2021) investigated the possible ecosystem and fishery impacts of dreissenid invasion on Shuswap Lake, British Columbia. They predicted that a high-density invasion would result in declines in resident Rainbow Trout (*Oncorhynchus mykiss*), Lake Trout (*Salvelinus namaycush*), and Kokanee Salmon (nonanadromous freshwater *Oncorhynchus nerka*), but would have little effect on anadromous Sockeye Salmon (*O. nerka*). Impacts of mussels are predicted to be limited in Shuswap lake due to the limited shallow-water habitat available and by the movement of fishes out of the system (either to the ocean, or to rear in rivers upstream of the lake). As a recreationally important lake, another risk of invasion to Shuswap Lake is that it may facilitate further invasions within British Columbia. Thus, preventing the spread of dreissenid mussels into the system continues to be imperative.

The relationship between genetic diversity and the success of invasive populations has been widely studied. Invasive populations may lose diversity, gain diversity, or remain constant over time. Marshall and Stepien (2021) compared the trends in genetic diversity for the congeneric *D. polymorpha* and *D. bugensis* over the course of their concurrent invasions of North America. The authors examined DNA microsatellite markers for populations in Lake Erie, Ohio, USA, and the Hudson River, New York, USA at three time points: 1994, 2003, and 2016. With different trends in the two species and locations, their results suggest that shifts in genetic diversity may be complex, with both genetic stasis and significant divergence possible in different populations in the invaded range.

Kingsbury et al. (2021) presented their study on prediction of invasive species distributions to prevent further spread and protect vulnerable habitats and species at risk (SAR) from future invasions. Their study focused on the freshwater Chinese mystery snail, *Cipangopaludina chinensis*, native of Eastern Asia and potentially invasive, widely established across North America, Belgium, and the Netherlands (Collas et al. 2017; Jokinen 1982; Kipp et al. 2021; Matthews et al. 2017; McAlpine et al. 2016). This species was first reported in Nova Scotia, Canada in 1955 but was not found to be established until the 1990s and now seems to be present at high densities in several urban lakes. The presence and the potential distribution of this species in Nova Scotia (NS) remains unknown, and limited resources make it difficult to do a broad survey of freshwater lakes across this Canadian province (McAlpine et al. 2016). Kingsbury et al. (2021) developed a species distribution probability model to focus on priority areas. They applied a random forest model with a combination of water quality, fish community, anthropogenic water use, and geomorphological data to predict *C. chinensis* habitat in NS. All NS habitats had predicted probabilities of being able to support *C. chinensis* > 50%, with the highest probabilities found for 3 regions: Cape Breton Island, the Nova Scotia-New Brunswick border, and in the Halifax Regional Municipality. Predicted suitable habitats for *C. chinensis* overlaps with many SAR habitats, most notably brook floater mussel, *Alasmidonta varicosa*, and yellow lampmussel, *Lampsila cariosa*. These results indicate that *C. chinensis* could become widespread throughout NS, appearing first in the aforementioned areas of highest probability. Further research is required to test *C. chinensis* ecological thresholds to improve the accuracy of future species distribution and habitat models, and to determine *C. chinensis* impacts on native freshwater mussels of conservation concern.

This issue concludes another successful ICAIS conference, summarizing many of the major threats to biodiversity loss in conjunction with climate change. The number of organisms that spread and invade new habitats has increased in recent decades because of drastic environmental changes (i.e., higher temperatures) and anthropogenic activities (Suescún et al. 2021). Bioinvasions occur worldwide in terrestrial and aquatic systems and represent an emerging challenge to our understanding of the interplay between biodiversity and ecosystem functioning (Suescún et al. 2021).

We hope ICAIS will continue to be a comprehensive forum where scientists, international organizations and stakeholders from all continents, working with different taxa can present their latest research to raise awareness of aquatic and terrestrial invasive species impacts and to prevent new introductions, both locally and globally.

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