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Special Issue: Invasive Species in Inland Waters

Editorial

Invasive species in inland waters: from early detection to innovative management approaches

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Invasive alien species are one of the major threats to biodiversity and the functioning of ecosystems (Vitousek et al. 1997; Garcia-Berthou et al. 2005), having serious consequences for the ecological status of inland waters. Once invasive species have become established in ecosystems, eradication is often an unachievable management goal. Therefore, scientific efforts should be directed at understanding the drivers of introductions of alien species and the mechanisms underlying invasion success. Data on invasion patterns and assessment tools are crucial to address emerging issues and to elucidate new perspectives for better understanding and cost-effective management of biological invasions.

In 2016, three important symposia on aquatic invasive species were organized, each of which provided useful insights into issues concerning their detection, ecology, and management. The 19th International Conference on Aquatic Invasive Species (ICAIS) was held in Winnipeg, Canada from April 10 to 14 and was hosted by the Western Canada Chapter of the International Society for Ecological Restoration (SERWC). ICAIS is widely recognized as the most comprehensive international forum on aquatic invasive species and continues to evolve and address new and emerging issues (Van der Velde et al. 2009; Lucy and Muckle-Jeffs 2010; Karatayev et al. 2012; Lucy and Panov 2014; Wong et al. 2017). In recent years, the conference has involved participants representing academia, industry, government, non-governmental organizations and other stakeholders, all dedicated to research on, and management of, aquatic invasive species. The theme of the 19th ICAIS was *Global Advances in Research and Management of Aquatic Invasive Species* (ICAIS 2016).

In addition, the Centre for Wetland Ecology (CWE) organized the symposium *The role of exotic species in aquatic systems*. This CWE symposium was held on June 24 at the Netherlands Institute of Ecology in Wageningen (The Netherlands). Dutch and Flemish water and wetland researchers participate in the CWE, which provides a network and scientific platform for research on ecology, biogeochemistry, microbiology, hydrology and restoration of wetlands and water bodies. The central theme of the CWE symposium was how alien aquatic plants and

animals impact ecosystem functioning and native flora and fauna. Finally, the 33rd Congress of the International Society of Limnology (SIL) was hosted in Turin (Italy) from July 31 to August 5, and devoted to *Science for a sustainable freshwater use*. A special session of this SIL congress was focussed on alien species' ecological impacts. Within this context, the European Virtual Biodiversity Research Infrastructure LifeWatch Italy promoted a European-level case study designed to assess the vulnerability of ecosystems to introductions of alien species. LifeWatch endorsed this SIL session aiming at a better understanding of biological invasions using genomic to macroecological approaches, and proposing innovative management strategies that limit invasive alien species presence to guarantee a wiser approach to biodiversity conservation.

Papers collected for the present special issue of *Aquatic Invasions* are representative samples of topics from the ICAIS, CWE and SIL meetings. Highlights of these studies are structured into five themes: 1) Early detection and monitoring of invasive species, 2) Drivers of biological invasions, 3) Factors determining invasion success, 4) Impacts on biodiversity and ecosystem functioning, and 5) Innovative management strategies to minimize the negative impacts of invasive species. In addition, selected ICAIS papers concerning technological developments and stressing the importance of international cooperation in the management of invasive species in inland waters are available in the special issue of the international open-access journal *Management of Biological Invasions* (Wong et al. 2017).

Early detection and monitoring of invasive species

Border and sea transport controls are important to prevent the introduction of invasive alien species. However, controls are never effective in all circumstances. Therefore, early detection is crucial to prevent the establishment and spread of newly arrived potentially invasive species. Collas et al. (2017) studied the early invasion of the Chinese mystery snail, *Bellamya* (*Cipangopaludina*) *chinensis* (Gray, 1834), in Western Europe and performed a risk assessment of this species using the Harmonia+ protocol. This freshwater snail was first detected in the European Union in 2007 and has since colonized twelve water bodies in the Rhine-Meuse River delta in the Netherlands. The population density in floodplain lakes was 0.33 individuals/m^2 and the dispersal rate approached 0.1 km/yr. The authors determined *B. chinensis* to have a high risk of introduction and establishment and a medium risk of spread and environmental impact. However, there is a knowledge gap concerning effects of *B. chinensis* on native biodiversity and ecosystem functioning, particularly at high population densities. To prevent new introductions and to slow the spread around Europe, several measures have been recommended: (1) regulate the trade of this species, (2) educate the general public about potential impacts, and (3) develop cost-effective management strategies (e.g., eradication, population control and containment measures).

Jansen et al. (2017) analysed the rapid geographic expansion of the invasive spiny water flea (*Bythotrephes longimanus*) in Manitoba (Canada) over the period 2009-2015. This species is well-known for its negative impacts on zooplankton in lakes, including reducing abundance and biomass, and displacing native species. Since its first record in 2009 in the Winnipeg River, the spiny water flea has spread throughout Lake Winnipeg. More than 60 sites within and adjacent to Lake Winnipeg were sampled to track its northward expansion using multiple sampling techniques (i.e., drift nets, kick nets, and benthic samplers). The findings of Jansen et al. (2017) suggest that the spiny water flea has colonized Lake Winnipeg from south to north (a distance of 431 km) over just two years. There is also evidence of downstream dispersal in the Nelson River, north of Lake Winnipeg, but the species has not yet been detected in other lakes further down the chain. Due to higher nutrient loads in the South basin of Lake Winnipeg, higher abundances of the spiny water flea, which prefers clear water, may be limited to the North basin. However, increasing water clarity resulting from the recent introduction of the invasive zebra mussel (*Dreissena polymorpha*) in Lake Winnipeg could potentially create more favourable conditions for the spiny water flea throughout the lake.

Drivers of biological invasions

The current scientific literature is not conclusive concerning the relative importance of propagule pressure, and abiotic and biotic variables as determinants of alien species presence. This limits generalisations of invasion patterns and processes. Colangelo et al. (2017) performed a macroecological assessment of drivers of occurrence of alien species (microorganisms, plants and animals) across several natural freshwater ecosystems in Italy. Propagule pressure, abiotic conditions and biotic characteristics were selected as predictors of the invasibility of a site. Propagule pressure and differences in the native species richness of the receiving community significantly explained the number of alien species

occurrences. Specific and local climatic conditions coupled with high site accessibility produced a relative higher risk of invasibility, confirming the role of abiotic filters in invasion processes. Moreover, both the biological features of the receiving community and of the invading taxa act in synergy with abiotic drivers and propagule pressure. Body size influenced the occurrence and colonization processes of alien species. Larger taxa are more likely intentionally transported by humans and are less subject to predation and to competition with the native community. Smaller taxa are frequently coupled with uncertainties associated with data collection (e.g., due to difficulties with sampling and identification) and classification as alien species (e.g., cryptogenic species).

Factors determining invasion success

Invasion success is determined by unique species traits and the vulnerability of ecosystems. Ashenden et al. (2017) assessed boldness and dispersal tendency of native North American and invasive European pumpkinseed (*Lepomis gibbossus*) to find out whether spatial sorting creates superior invaders. Tests were conducted in an artificial flume with a video capture system recording the movements of the pumpkinseed. Boldness was measured using the time it took an individual to emerge from a sheltered area, and dispersal tendency was assessed using a combination of movement metrics as the fish explored the flume. Contrary to expectations, native North American populations were bolder than invasive European populations, and there was no significant difference in dispersal tendency between native and invasive pumpkinseed. Interestingly, post-hoc analysis indicated that populations originating from lotic water bodies had significantly lower dispersal tendency than those from lentic water bodies regardless of native or invasive status. This result suggests that habitat of origin may affect dispersal tendency of alien fish species.

The toxic cyanobacterium *Cylindrospermopsis raciborskii* has spread into aquatic ecosystems of almost all continents with temperate climate zones. Its invasion success has been explained by environmental factors such as temperature, light and nutrient levels. Weithoff et al. (2017) elucidate the importance of genetic identity, grazing loss, competition and biotic resistance for the invasion success of this species. The invasiveness of three different isolates introduced into natural plankton communities under three grazing levels was tested using laboratory mesocosm experiments. Only one of these isolates persisted in the plankton communities at a rather low level in the absence of larger zooplankton. Thus, under suitable environmental conditions, top-down control from zooplankton might hamper the establishment of *C. raciborskii*. Differential grazing impact shaped the resident community in different ways allowing this cyanobacterium to invade under low grazing pressure. Even in the case of invasion failure, its temporary presence induced changes in the phytoplankton community (legacy effect).

The Australian swamp stonecrop (*Crassula helmsii*) rapidly invades moorland pools and small lakes in the Netherlands, Belgium and United Kingdom. Brouwer et al. (2017) conducted indoor experiments to test the competitive strength of this species under terrestrial conditions with nutrient-poor moorland soil in comparison with that of two characteristic moorland species in northwest Europe (i.e., *Littorella uniflora* and *Hypericum elodes*). The total cover of *C. helmsii* increased gradually in monocultures, until after 7–20 weeks a maximum of 12–20% was reached. Nitrogen content of the plants was very low at the end of the experiment and adding nitrogen increased its cover. However, in the mixed cultures, *C. helmsii* fared worse than the native species, indicating that the native species are better competitors for nutrients than *C. helmsii* due to their larger root system.

Invasions of (sub)tropical aquatic plant species threaten biodiversity, affect functioning of ecosystems and may also cause economic impacts in temperate regions. A relevant question is whether native herbivores are able to provide biotic resistance and inhibit the invasiveness of (sub)tropical species. Petruzzella et al. (2017) conclude that there is potential for biotic resistance from native generalist herbivores to (sub)tropical invasive plants in aquatic ecosystems of temperate areas. Field studies are scarce but available literature demonstrate that native herbivores, such as beavers, coots or generalist insect herbivores, significantly reduce the invasion success of (sub)tropical plant species. Tropical plants are nutritionally poor and better defended (i.e., less palatable) compared to temperate plants, but in the majority of laboratory feeding trials, herbivores eat (sub)tropical plants as much as temperate plants.

The host range expansion of the specialist milfoil weevil, *Euhrychiopsis lecontei*, is one of the few examples of a native insect herbivore growing and surviving better on an alien host plant than it does on its native host plant. Marko and Newman (2017) studied the fecundity of this milfoil weevil on its native host plant *Myriophyllum sibiricum* (Northern watermilfoil), the invasive alien *M. spicatum* (Eurasian watermilfoil) and hybrid watermilfoils in

relation to plant chemistry. The milfoil weevil had higher fecundity and preference for oviposition on Eurasian watermilfoil in comparison with northern watermilfoil. These responses were related to differences in plant chemistry and decreased when plants from common environments were used. A complete host switch appeared to be unlikely because most weevils continued to use both hosts.

Impacts on biodiversity and ecosystem functioning

Biological invasions and climate change affect the persistence of native species and pose risks to functioning of shallow aquatic ecosystems. Grutters et al. (2017) studied the effects of native and alien freshwater plant species on methane emission and phytoplankton growth in mesocosms. Plant growth in warm eutrophic conditions varies strongly with their identities and determines whether the replacement of native by alien plant species will alter ecosystem functions such as regulation of phytoplankton growth and methane emission. Native and alien plant species with similar traits do not differ in their regulation of phytoplankton growth and methane emission, in the interaction with periphyton or in the provisioning of refuge and food for invertebrates.

Stiers and Triest (2017) studied the effects of three invasive alien plant species (*Hydrocotyle ranunculoides*, *Ludwigia grandiflora* and *Myriophyllum aquaticum*) on phytoplankton and zooplankton of temperate ponds. Zooplankton density was negatively related to the coverage of invasive plant species. This effect was possibly due to low dissolved oxygen concentrations, physical obstruction and a putative allelopathic property of the invasive plants. Biovolume of phytoplankton was not correlated with invasive plant cover, although dominance of functional groups differed (e.g., species with tolerance to low light availability dominated in invaded ponds).

Several alien crayfish species have been introduced into European inland waters as they have commercial value as food or fish bait. Attempts to achieve good ecological status of water bodies can be frustrated by the presence of invasive crayfish species due to cutting stems of plants and bioturbation of sediment. Roessink et al. (2017) show that *Orconectes virilis* negatively affects macrophytes and water quality when their densities are equal to or higher than 1.25 individuals/m^2. No effects were observed when the density of crayfish in fully established systems was at 0.63 individuals/m^2. However, a start-up phase with emerging plants after winter season may be less robust, even at these low densities.

Innovative management strategies to minimize negative impacts

Regulated rivers are often dominated by man-made hydro-engineering structures of basalt stones and rip rap. These habitats have rapidly been colonized by invasive alien species such as the round goby (*Neogobius melanostomus*). Recently, managers have tried to restore natural complex large wood habitats by installing large trees under water in littoral zones. Dorenbosch et al. (2017) investigated whether the application of large wood in regulated riverine habitats favours native fishes over invasive round goby, Round goby can reach high densities in habitats with hard substratum, thereby negatively affecting native benthic species. Entire trees were anchored horizontally at four sites (two in the littoral zone of the river and two in the floodplain lake) on the sandy river bottom close to groynes constructed from basalt stones. Differences in fish assemblage between large wood sites and reference sites were assessed; and also compared to data collected in nearby sites in previous years. In large wood habitats, counts of native fishes were significantly higher than those of round goby, while the opposite was true in the reference sites. Total number of fish specimens did not significantly differ between habitat types. These results suggest that large wood in regulated rivers predominantly functions as an attractive habitat for native fishes and only to a small extent to round goby. Therefore, large wood may be applicable as a management tool to stimulate native fish fauna.

Concluding remarks

The present special issue of *Aquatic Invasions* underlines that early detection as well as monitoring of alien species is relevant for analysing invasion patterns and understanding invasion processes in inland waters. Studies on drivers, success factors and impacts of biological invasions are crucial to perform sound risk assessments of alien species and to derive innovative strategies for eradication or control of invasive species. International cooperation among competent authorities, researchers and managers is essential to extend our body of knowledge on aquatic invasions and to implement cost-effective management measures. However, many invasive alien species are already widespread. Eradication of these species often appears to be technically unfeasible or will not be cost-effective. Therefore, innovative measures are required to control the spread and to mitigate the negative impacts of invasive alien species. Future research and meetings should disentangle key

factors for their invasion success and derive ecosystem-based management strategies for conservation of native biodiversity without facilitating invasive species.

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