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T4.2.2. Role of barriers in managing aquatic invasive species

Jeroen S. Tummers*

Martyn C. Lucas

University of Durham, UK

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*: j.s.tummers@durham.ac.uk

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Summary

Modification of river systems by humans, with the purpose of, for example, irrigation, electricity generation, navigation or flood control, severely fragments freshwater habitats and is widely acknowledged to affect the ecological integrity of river systems. However, with an increasing frequency of river system invasions by non-native species comes the need to control the spread of aquatic invasive species (AIS). Construction of barriers to intentionally fragment river habitats or the decision to not remove existing ones may be needed to control AIS when eradication is unfeasible, whereby harmful, non-native species should be prevented passage over the barrier while locally occurring biota should not be hindered in their free movement. Therefore this represents an increasingly significant aspect in the adaptive management of barriers in rivers, and should form part of the decision process for removing barriers, building new ones, or installing biota passes. Increasingly the concepts of 'intentional fragmentation', 'management by isolation' and 'selective passage' are being adopted in river catchments threatened by the spread of AIS. In rivers, plants and microorganisms generally spread passively with the flow or are carried by mobile organisms, whereas some animals are capable of upstream spread, control of which may be possible in some cases using barriers. Selective passage is based on the concept of ecological filters which act on biological traits similar to different parts of a niche space. In this report, a global review is presented of how barriers of different types (e.g. physical, physiological, behavioural) are used to control the spread of AIS, of which physical barriers are most pertinent to the AMBER project. In an evidence-based approach, barriers acting on a range of biological traits are discussed for their effectiveness in limiting the expansion of invasives in the freshwater environment while still allowing free movement by native biota. Based on a scoring system used for invasive species' impact in Europe, invasive freshwater biota for each major taxonomic group are addressed and recommendations are given on how to manage those respective biota adequately using barriers. This report aims to contribute to raise awareness for exotic freshwater species with freshwater managers, and to help understand how to control the spread of such invasive animals while keeping wider ecosystem impacts to a minimum.

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1. Importance of connectivity for biota

Increased landscape connectivity has widely been recognized as crucial for the survival of a wide range of terrestrial organisms, which are dependent on food availability, habitat quality and configuration of suitable, connected habitat within the landscape for free movement (Galpern *et al.* 2011; Minor and Gardner 2011; Haddad *et al.* 2015). The ability to move freely across landscapes is required for locating foraging and resting grounds, and for seeking shelter against predation or adverse environmental conditions. It is also crucial for periodic migrations for reproduction (Brodie *et al.* 2015). With increasing anthropogenic influences to the natural environment (e.g. fences, road networks and urban developments), habitats are becoming smaller and more isolated and as a result, species are more likely to decline (Didham 2017; Tucker *et al.* 2018). Increasing the connectivity, size and number of habitat patches or networks of protected areas may provide refuges for species moving across the landscape, and corridors for much-needed dispersal opportunities between protected areas (DeFries *et al.* 2007; Hole *et al.* 2009; Baxter-Gilbert *et al.* 2015). Preservation of these movement pathways so as to modify habitat isolation, in order to mitigate negative effects of fragmentation and restore lost habitat has been widely attempted by creation of wildlife corridors (Haddad *et al.* 2015).

Considering aquatic environments, the importance of connectivity is especially high given the linearity within the (dendritic) profile of river systems. In intensely developed rivers, hydrologic pathways may become fragmented by construction of weirs, dams and water diversion structures, while animals depend on free movement within aquatic systems (longitudinally, but potentially also laterally to floodplains) for foraging, seeking shelter, reproduction and nursery areas (Lucas and Baras 2001). Equally, dispersal is a crucial process for all organisms, including plants and microorganisms. By reconnecting fragmented habitats, biodiversity is often enhanced due to metapopulation processes occurring more frequently, and through restoration of gene flow among populations (Fullerton *et al.* 2010) and by reinstating natural river processes that support habitat diversity downstream of former river obstacles. Compared to movement in the terrestrial environment, or even in large open, slow-moving aquatic environments (marine, lacustrine), the movement of many river organisms is normally constrained to within the river channel and floodplain. Upstream movement of many biota except large free-swimming organisms such as fishes is quite restricted (Kappes and Haase 2012). Even for most fishes, their ability to overcome in-river obstacles such as dams, weirs, culverts is often relatively poor, especially in an upstream direction (Hall *et al.* 2011). Downstream movement of plants and animals past barriers is less affected in general, but can still be determined by the hydrological conditions and by behavioural responses to

animals to such structures (Zhang *et al.* 2007). The movements of some groups, such as aquatic insects with a winged imago stage, are much less affected by physical barriers (Tonkin *et al.* 2014; Sondermann *et al.* 2015). To enhance hydrologic connectivity in river restoration (e.g. in the REFORM project - <https://reformrivers.eu/>), a variety of mechanisms have been adopted widely, including the removal of infrastructure, reducing the impeding effect of in-river structures on free movement by installing various types of fishways and other biota passage corridors (Verástegui *et al.* 2017; Silva *et al.* 2018) and changing reservoir management so that more natural flow regimes are adopted (Schmidt and Wilcock 2008).

Benefits on populations of aquatic wildlife of reducing habitat fragmentation by riverine infrastructure or even complete removal of such anthropogenic features have been well documented (e.g. Birnie-Gauvin *et al.* 2017; Drouineau *et al.* 2018; Watson *et al.* 2018). Management of aquatic systems should be undertaken carefully and requires a well-grounded decision making process, whereby a framework is needed that incorporates impacts of altered water-mediated transport of abiotic (nutrients, sediment, toxins, energy) and biotic (invasive species) components (Pringle 2006). Ecological considerations to take into account include preventing or limiting range expansion of invasive species, preventing the spread of diseases, preventing individuals from entering ecological traps and preventing genetic mixing (hybridization) of wild and stocked (hatchery-origin) populations, and these considerations should be balanced against the benefits of increased hydrologic connectivity (Jensen and Jones 2017; Milt *et al.* 2018). It is thus possible that, after analysis of such trade-offs of environmental effects in intensively developed aquatic systems, it may be preferential to maintain (or even further reduce) connectivity within waterways so as to minimize ecological impacts, especially in systems affected by, or with a history of, invasive species (Rahel 2013; Starrs *et al.* 2015). The ecological (and economic - Lovell *et al.* 2006) impacts of aquatic invasive species (AIS) on river systems have been extensively studied globally for a broad number of invasives (e.g. Peterson *et al.* 2008; Shibata *et al.* 2011; Van der Walt *et al.* 2016; Pereira *et al.* 2017; Gobel *et al.* 2019), and warrant the need to be acknowledged a top priority in catchment based management protocols (Wittmann *et al.* 2014; Pereira *et al.* 2018; Xiong *et al.* 2018).

2. Ecological impacts of invasive species

Biodiversity of freshwater ecosystems is in decline globally (Dudgeon *et al.* 2006), in part attributed to the consequences of biological invasions (Kitano 2004; Strayer and Dudgeon 2010; Simberloff and Vitule 2014), the spread of which has been facilitated considerably by human-induced actions

including directly by connecting and opening of historically isolated waterways on large spatial scales, but also on small scales such as removal of river infrastructure, and indirectly by (long-distance) inter-basin transfers (on ship hulls, in ballast water; Leuven *et al.* 2009; Keller *et al.* 2011; Kelly *et al.* 2013). The invasion process is constituted of four stages; transport (displacement across major geographic barriers to invasion area, success dependent on survival rate of offspring), colonization (environmental conditions at the arrival site must be within tolerance range), establishment (crucial to survive natural enemies, potentially form mutualistic relationships and acquire resources) and landscape spread stage (expanding presence by establishing colony populations), each of which is crucial for a species to become invasive (Hellmann *et al.* 2008; Gallardo *et al.* 2016; Coulter *et al.* 2018). In freshwater, invasives often have generalized habitat requirements and may tolerate low dissolved oxygen concentrations and/or altered water quality, which facilitates their ability to displace and replace native fauna (Alonso and Castro-Diez 2008; Lodge *et al.* 2012). Thus, alterations to rivers, including damming, often generate habitat conditions in a which a proportion of alien species colonise and spread to become AIS, at the expense of native species, reducing the resilience of the ecosystem. Climate change may impact aquatic systems as well (Rahel *et al.* 2008), and may even potentially have a synergistic effect with ecological impacts by non-native species, because it may affect the distribution, spread, abundance, and impact of invasive species (Gritti *et al.* 2006; Hellmann *et al.* 2008; Roberts *et al.* 2017; Bae *et al.* 2018).

Multiple non-indigenous species may have an interactive effect on the community and ecosystem invaded (Ficetola *et al.* 2006; Johnson *et al.* 2009). Aside from the environmental impact, AIS may have an adverse effect directly to humans in the form of monetary losses, or may impact social structure (Charles and Dukes 2008). Ecological integrity may be affected through trophic cascades, whereby the newly introduced functional components (i.e. invasives) cause ecological impacts throughout the food chain (Strayer 2010) via top-down (Mercado-Silva *et al.* 2009) or bottom-up (Lodge *et al.* 2012; Heath *et al.* 2014) control of the food web. While direct biotic interactions between invader and indigenous species through predation, competition or grazing are more widely known (e.g. Rösch *et al.* 2018; Gobel *et al.* 2019), alterations in habitat conditions may affect the recipient community as well (e.g. Zaiko *et al.* 2007). Such habitat conditions (e.g. nutrients or water clarity) may be changed dramatically and at high intensity by invasive ecosystem engineers, thereby affecting population persistence of non-tolerant endemic species severely (Darrigran and Damborenea 2011; Sousa *et al.* 2014). While in some cases, AIS may have a perceived beneficial effect, for example zebra mussel *Dreissena* clearing eutrophic, turbid water (Caraco *et al.* 1997), negative impacts may still persist (e.g. the commercial impact of fouling by zebra mussel). Although

the impacts of aquatic invasives, potentially constituting a broad spectrum of taxa, are widely recognized, freshwater managers often fail to address them sufficiently in order to protect regional biotic integrity (Tsuboi *et al.* 2013; Moorhouse and Macdonald 2015). One of the most efficient measures in managing AIS in order to control the spread of invasive species entails reducing the connectivity among habitats by barriers (Kates *et al.* 2012; Rahel 2013; Sherburne and Reinhardt 2016).

3. Barrier management to exclude non-natives

Management of AIS requires an integrated and coordinated approach incorporating multiple elements. These include effective legislation and education to prevent the release of non-native species outside their natural range; predictive tools to classify and rank those species at greatest risk of becoming invaders; effective surveillance to identify invasions early on, and effective management measures to eradicate or control AIS (Koehn and MacKenzie 2004; Van der Zanden and Olden 2008; Hussner *et al.* 2017). River barriers have the potential to contribute towards management of the spread of AIS.

Where existing barriers occur within an invaded catchment, the distribution, type and permeability of those barriers form a key tool for the management of within-catchment invasion. Almost all river biota have one or more life stages which facilitate downstream movement, often by way of “drift” on water currents and contribute to dispersal and recolonization (Kennedy *et al.* 2014; Lechner *et al.* 2014). Thus the use of barriers to manage AIS is mostly limited to inhibiting their spread upstream. Since many aquatic plants and bacteria have passively drifting propagules that are effectively incapable of upstream movement, their independent spread upstream of a colonisation point is unlikely whether a barrier is present or absent immediately upstream. Instead, spread is likely to be via propagule contamination of vectors such as waterbirds (Figuerola *et al.* 2003) or boats (recreational or commercial; Donnelly and Walters 2008) and lentic habitats upstream of dams may provide conditions for multiple point-source colonisation and subsequent downstream spread from each. As such, it can be theorised that in impounded reaches upstream of the range of passively dispersing IAS, dam removal is more likely to inhibit spread of passive dispersing species, especially lacustrine ones. By contrast, the spatial distribution of barriers sufficient to prevent upstream dispersal and colonisation is increasingly applied in catchment management to inhibit upstream spread of actively dispersing animals. A GIS framework may be developed to assess management options within a catchment in combination with barrier network algorithms (King and O’Hanley 2016) so that the spread of invasives may be mapped and limited adequately.

At the early invasion stages, invasives should be prevented from dispersing to a new region or, once introduced, should be prevented from secondary spread from the introduction point, which may be achieved by strategic placement of barriers (Dana *et al.* 2011; Clarkson *et al.* 2012), especially for limiting natural spread further up the catchment. Even small barriers may potentially prove adequate in protecting local endemic communities (e.g. Pratt *et al.* 2009; Rosewarne *et al.* 2013; Miehl *et al.* 2017). A common approach when invasive species have such strong biotic or abiotic interactions with the receiving community that coexistence is unrealistic, is the use of intentional fragmentation, whereby a barrier is constructed, non-native taxa are removed upstream of the barrier (if they have already arrived there) while native species are returned to and/or stocked in upstream reaches (Neeson *et al.* 2015). This strategy, also known as isolation management, is particularly relevant and needed when a non-native species has reached the establishment invasion phase when elimination has become unfeasible, and the focus for freshwater managers changes to population control (Fausch *et al.* 2009). When barriers are constructed, novel habitat may be created, which can be beneficial for invasives to colonize (Liew *et al.* 2016). Upstream of barriers, the conversion of natural lotic segments into artificial lentic habitat may impact rheophilic species which are intolerant to drastic changes in environmental conditions, after which invasives may fill these new niches (Liu *et al.* 2012; Vitule *et al.* 2012). Non-specialist habitat requirements and a tolerance for changed water quality, altered water temperature regimes or low dissolved oxygen may also explain the increasing presence of non-native species in tailwater areas of dams (Linares *et al.* 2018; Pereira *et al.* 2018; Xiong *et al.* 2018). Indeed part of the argument made for removal of barriers in restoration of rivers with non-natives is that it may restore conditions to those closer to which native species are adapted and enhance their ability to compete favourably with non-natives (Stanley and Doyle 2003; Fausch *et al.* 2009). A careful approach, as shown in *Figure 1*, should therefore be taken by freshwater managers when the decision is made to construct barriers.

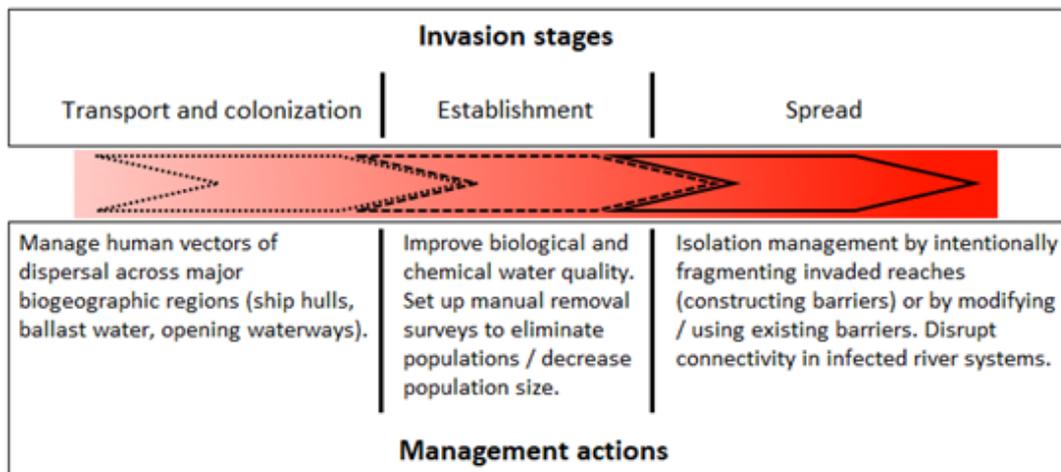


Figure 1: Invasion stages and possible management actions during the process of an aquatic invasion.

Reducing hydrologic connectivity in river systems is known to adversely affect animal populations (e.g. Magilligan *et al.* 2016; Silva *et al.* 2018; Liu and Wang 2018). Ideally, intentional fragmentation should still allow for free movement of native biota, while blocking or limiting passage of undesirable, invasive species (e.g. Starrs *et al.* 2015; Sherburne and Reinhardt 2016). This concept of selective passage has only recently received more attention (e.g. McLaughlin *et al.* 2013; Moran-Lopez and Tolosa 2017), whereas historically biota (usually fish) passage efforts were almost always focused on facilitating migration of juveniles of target species to nursery areas and adults to spawning habitat (Clay 1995). For fishes, a small portion of each population may move relatively long distances (Radinger and Wolter 2014), meaning invasive species may be able to rapidly spread to new areas if connectivity is not adequately reduced. Achieving well-functioning selective passage over barriers is dependent on the differential ability of species to meet, or fail to meet, one or more ecological criteria designed to filter out invasive species from desirable species in impacted reaches (Pelicice *et al.* 2015; Kirk *et al.* 2016). Biological traits, which determine the capacity for organisms to move over or through a barrier (e.g. physical, physiological or sensory barrier; Noatch and Suski 2012) are used as focal points for ecological filters (Mims and Olden 2013; Bajer *et al.* 2015).

4. Selective passage by animals over barriers based on biological traits

The following sections refer to design principles for developing selective passage for animals and emphasize control of active upstream movement as part of intentional isolation management methods. Most of the principles are illustrated by reference to fishes, for which the best and by far the most examples are known, although the broad principles are relevant to other river animal biota too. Although most of the examples currently available relate to limiting upstream movement, the principles can also be applied to lateral connections and downstream movement, although for the latter especially 'drift' dispersal and colonisation makes that more difficult.

4.1. Physical attributes

Barriers may work effectively by selecting on biota locomotion, which includes swimming, jumping and climbing. Swimming capacity balances between endurance and speed, and multiple swimming speed categories exist. In increasing velocity, long-distance, aerobic swimming at optimal swimming speed (U_{opt}), critical swimming speed (U_{crit}) with maximum oxygen uptake and finally anaerobic burst swimming which can only be used for up to several seconds and defined as maximum swimming speed (U_{max}) (Videler 1993; Tudorache *et al.* 2008; Guderley and Pörtner 2010; Kieffer 2010). While flow regimes over barriers and through fishways may be complex with, for example, the occurrence of high turbulence under moderate to high discharge levels and low velocities observed in channel

margins even under high flow conditions, structures such as fishways may be constructed so that the combination of flow velocities and fishway or barrier length may filter out invasive species in upstream reaches. There are some species which are able to withstand higher current velocities by employing a low-energy, recovery strategy of holding in place and for it then to resume upstream ascent with partially replenished energy levels. Examples include lamprey (*Petromyzontiformes*) able to attach to surfaces employing a burst-attach-rest behaviour (Vowles *et al.* 2017), and non-native European round gobies (*Neogobius melanostomus*) which use their pectoral and modified pelvic fins to hold station at higher current velocities (Tierney *et al.* 2011).

Jumping ability of aquatic biota (almost exclusively fish) constitutes another selective filter, as fish differ in their maximum jumping height, dependent on several factors including species, body size, water depth and water temperature (Ficke and Myrick 2011; Baudoin *et al.* 2015). A barrier which requires fish to jump in order to traverse it, may thus filter out certain species which have a lower jumping ability. Perhaps the best known example of this is the use of lipped weirs in the Laurentian Great Lakes to prevent upstream passage of non-leaping sea lamprey (*Petromyzon marinus*), while allowing passage of jumping salmonids, but unfortunately not the passage of many other non-jumping native migrants such as many cyprinids and catostomids (Pratt *et al.* 2009). Such approaches require an understanding of the jumping ability of native and non-native species. For example (Holthe *et al.* 2005) defined the obstacle height necessary to prevent successful jumping by invasive Eurasian minnow (*Phoxinus phoxinus*) in Norwegian rivers dominated by leaping salmonids. Common carp (*Cyprinus carpio*) are not conventionally known for their leaping ability, but in Australia this species was effectively filtered out from endemic species in confinement at traps placed at dams and weirs by exploiting their unique jumping behaviour with a cage device (Stuart *et al.* 2006).

Climbing is a behavioural technique used by Pacific lamprey (*Entosphenus tridentatus*) in North-America as reported in Frick *et al.* (2017). This species attaches to substrate with its sucker mouth, flexes its body in a waveform, then extends upward and reattaches. Passage success was high (94%) over a 1.6 m high aluminium wetted weir. As the capacity to use climbing behaviour to overcome barriers is rare among fishes (Zhu *et al.* 2011), though it is widely adopted in anguilliform eels it has the potential to be used as a trait for selective passage (Goodman and Reid 2017). Limiting walking and climbing ability of invertebrates without an aerial life stage is a potential option and has been proposed for crayfish (Kerby *et al.* 2005; Dana *et al.* 2011; Rosewarne *et al.* 2013) based upon reduced propensity to climb upstream over smooth surfaces with low friction and/or at high

velocities and/or over vertical or lipped barriers. Frings *et al.* (2013) found that signal crayfish (*Pacifastacus leniusculus*) employed short swimming events as well as walking to facilitate passage, requiring a combination of steep gradient and sufficient flow velocity to prevent passage, yet other studies have not reported obstacle passage by swimming in crayfish and the importance of swimming in passing obstacles in nature has probably been overstated by Frings *et al.* (2013). It has been suggested that existing river barriers may be ineffective in blocking the upstream spread of decapod crustaceans because many species can temporarily leave the water and walk around the barrier, but this has not been demonstrated other than in anecdotal circumstances, and is dependent upon the barrier size, channel edge characteristics and hydrologic conditions.

4.2. Physiological attributes

As species have different optimum temperatures, progressive warming of aquatic habitats may cause shifts in phenology, distribution and abundance of invasive and native species by limiting oxygen transport systems when approaching maximum aerobic scope (e.g. Norin *et al.* 2014; Hesselschwerdt and Wantzen 2018). Animal taxa are regularly classified into thermal guilds, and temperature tolerance may be used in controlling invasive species (Null *et al.* 2013). Invasives falling into warmwater-adapted species may be prevented from entering reaches if water temperatures are low enough and vice versa (Kernan 2015), so that thermal tolerance may be used as an ecological filter in blocking invasive species (Hesselschwerdt and Wantzen 2018).

Reducing the oxygen concentration in the water column, or hypoxia, is another strategy working on the physiological state of organisms which may be used to limit the spread of invasives (Domenici *et al.* 2013). There is also evidence of potentially increasing oxygen concentrations to above normal levels (hyperoxia), which may be used as a control trait (Wheatly 1989). Since tolerance of a species to hypoxia and hyperoxia is dependent on its physiology and behaviour, the impact may be variable among species (Chapman and McKenzie 2009). Management of reservoir water quality through lowering oxygen content and lowering pH has been used as a successful management measure for achieving high mortality of invasive molluscs such as the Asiatic clam (*Corbicula fluminea*; Wittmann *et al.* 2012) and to slow population growth in crustaceans such as signal crayfish (*Pacifastacus leniusculus*; Wheatly 1989) and virile crayfish (*Orconectes virilis*; France 1993), but it has not acted as an absolute barrier (Sousa *et al.* 2014).

Exploiting the sensitivity of AIS to supersaturated concentrations of carbon dioxide may effectively limit the spread of AIS (Cupp *et al.* 2018; Schneider *et al.* 2018). Kates *et al.* (2012)

evaluated the effectiveness of increased CO₂ concentrations in water for deterring fish movement, for invasive species (silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*)), and native (to North America) species (largemouth bass (*Micropterus salmoides*) and bluegill (*Lepomis macrochirus*)). It was concluded that zones of elevated CO₂ have potential to deter the movement of fishes, though native species were also, but to a lesser degree, impacted. Similar impacts of elevated CO₂ were reported by Manea and Leishman (2011), who studied 14 native-invasive exotic plant species-pairs under ambient and elevated CO₂ exposure. Both native and invasive species were impacted by higher concentrations, but native-invasive comparisons revealed that exotic, more-competitive species had higher relative growth rate and net assimilation rate (Manea and Leishman 2011). This wider non-target species effect was not found for adult freshwater mussels (*Fusconaia flava*), which were found to experience limited physiological impacts from elevated CO₂ levels (Hannan *et al.* 2016).

4.3. Morphological attributes

In New Zealand, Daniel *et al.* (2014) evaluated the effectiveness of using a one-way fish barrier for common carp. Horizontal bars of 30 mm bar spacing successfully prohibited adult carp and eels to move upstream past the barrier. Although juvenile invasive carp were able to pass upstream, it was deemed impractical to design a barrier capable of blocking all invasives considering the conflicting need to provide free passage for native species. Furthermore, in a laboratory trial, selective passage was shown for common carp (Thwaites *et al.* 2010). When confronted by barriers, carp often attempt to jump over or push through them. Considering their relatively strong body morphology, a push trap element exploiting the pushing capacity of carps selectively filtered out invasive carp from native fish (Thwaites *et al.* 2010).

4.4. Behavioural attributes

The position in the water column at which fish swim may be used to selectively pass or exclude fish. Bottom orifices may selectively pass bottom-dwelling fish (to, potentially, capture and remove from the system; Jager *et al.* 2016). Selective passage based on diel activity has potential when managing AIS with barriers, as species may be distinctively nocturnal or diurnal (Johnson *et al.* 2016).

4.5. Sensory attributes

Sound may be used as a source for deterring or guiding invasive species in impacted water systems (Noatch and Suski 2012). Silver carp were shown to keep away from complex broadband sound sources, so that such acoustics may be used to selectively pass this species (Vetter *et al.* 2015). In a

laboratory experiment, Zielinski *et al.* (2014) demonstrated the effectiveness of bubble curtains (of three different levels of coarseness) on common carp movement behaviour. In the two coarser bubble trials, movement across the curtain was reduced by 75-85% in both directions, whereby the deterrent effect was a result of fluid motion and sound rather than visual cues. Invasive sea lamprey were found to be limited in their upstream movement by the use of low-frequency acoustics, strobe lights and a bubble curtain (Miehls *et al.* 2017).

Another sensory attribute which may be exploited in invasive species management is electricity. Electroreceptive organs are present on the head or as part of the lateral line system in cartilaginous fishes, teleosts and often in amphibians and used for locating prey (Northcutt *et al.* 1994). Over-stimulating the electroreceptors by use of strong magnetic fields as a nonphysical barrier may cause a repellent effect, thereby allowing selective passage (Gibbs and Northcutt 2004; Bajer *et al.* 2018). Spinycheek crayfish (*Orconectes limosus*) movement was found to be blocked by installing an electricity barrier (Benejam *et al.* 2015). Similar findings of electric barrier effectiveness on invasive species movement were documented by O'Farrell *et al.* (2014) and Johnson *et al.* (2016).

Olfactory sense has the potential to be used to filter out invasive species, as in the case of the invasive sea lamprey, which may be attracted towards, or lured away, from pheromone plumes (Meckley *et al.* 2014; Hume *et al.* 2015; Sorensen 2015; Wagner *et al.* 2018). Based on a controlled field trial in Australia, Hagman and Shine (2009) reported that alarm pheromones secreted by injured larval cane toads caused a reduction in tadpole survival rates, and tadpoles under repeated exposure of the pheromone did not seek shelter. The authors recognize larval pheromones as a means to control cane toad recruitment in nature, although more research is needed. From a field test, Wagner *et al.* 2006 demonstrated the effect of a migratory pheromone in luring sea lamprey towards a pheromone-baited trap. A high proportion (90%) of migrating individuals were drawn to pheromone-treated streams.

Application of a metal as a contact-deterrent substrate barrier has been tested to block the spread of the invasive New Zealand mudsnail (*Potamopyrgus antipodarum*; Hoyer and Myrick 2012). Copper-based substrates were shown to limit locomotor activity of the mudsnail under a set of water velocities and temperatures, pH values, hardness levels and levels of surface fouling.

To summarize, physical and non-physical barriers to free movement of invasive aquatic biota come in many forms and vary in effectiveness. Physical barriers may not always keep their impact on

the fitness of native species at a low rate (e.g. injury from exclusion bar screens), whereas non-physical barriers typically cause less injury and do not hinder navigation or constrain water flow (Noatch and Suski 2012). If a barrier is determined to be ineffective for managing alien species, combining multiple types of barriers may result in an arrangement able to greatly limit or even stop the spread of invasive species (e.g. McLaughlin *et al.* 2007; Miehl *et al.* 2017) which would benefit freshwater managers.

5. Invasive aquatic biota in Europe: impacts and control

Effective management of freshwater invasive biota requires knowledge on their abundance and rate of spread at appropriate spatial and temporal scales. For this report, invasive species in Europe are presented according to their impact (*Table 1*). A semi-quantitative tool (generic impact scoring system (GISS)) was used which reflects evidence of impact of invasive species. Twelve categories are distinguished each ranging from 0 (no impact detectable) to 5 (the highest impact possible) for a total possible score of 60 (highest impact; Nentwig *et al.* 2016; 2018). The table summarizes the potential for using physical and non-physical barriers for managing the spread of these invasive fishes, together with references to further information. Inevitably, not all species are included in the list since the perceived impact of different species varies from locality to locality and is changing with time. For example, the wels catfish *Silurus glanis* is native to parts of Europe but has been introduced to other parts of Europe, often for recreational angling. Where it was introduced and is successfully breeding it has become a major non-native apex predator causing concern as to its impacts. It has been introduced to many reservoirs above dams, which provide suitable habitat, but in the River Garonne, SW France, individuals have also been found to inhabit fishway pools preying on migrant species (Boulêtreau *et al.* 2018). Although some IAS, such as common carp are widely naturalised, they are non-native and widely acknowledged for the extent of their impact in floodplain systems (Vilizzi *et al.* 2015).

Table 1: Freshwater invasive species in EU, listed are up to 10 species per taxonomic group with highest ecological impact, based on the top 100 EU invasive species list as presented in Nentwig *et al.* 2018. Species are ordered from high to low impact based on the generic impact scoring system (GISS). Reptilia are not included in the table due to low scores on the GISS system.

Taxonomic group	Family	Total impact (GISS score; [0 – 60])	Type of barrier and condition acted on. Barrier types potentially linked to physical barriers such as dams, weirs and their management (e.g. water quality, sensory characters are in bold and underlined)	References
• Plants				
<i>Heracleum mantegazzianum</i> – Giant hogweed	Apiaceae	24	Chemical barrier (herbicidal control zones) ^{a,b}	Caffrey and Madsen 2001 ^a ; Nielsen <i>et al.</i> 2005 ^b
<i>Crassula helmsii</i> – New Zealand pygmy weed	Crassulaceae	22	<u>Physiological barrier (inundation with seawater^{a,b}; changes in water temperature^c)</u>	Charlton <i>et al.</i> 2010 ^a ; Gardiner and Charlton 2012 ^b ; Anderson <i>et al.</i> 2015 ^c
<i>Fallopia japonica</i> – Japanese knotweed	Polygonaceae	21	Chemical barrier (phloem-mobile herbicides control zones) ^a	Bashtanova <i>et al.</i> 2009 ^a
<i>Hydrocotyle ranunculoides</i> – Floating pennywort	Araliaceae	19	Chemical barrier (herbicide ^a), <u>Physiological barrier (draining^b; changes in water temperature^c)</u>	Newman and Dawson 1999 ^a ; Hussner and Meyer 2009 ^b ; Anderson <i>et al.</i> 2015 ^c
<i>Ludwigia grandiflora</i> – Water primrose	Onagraceae	19	Chemical barrier (herbicidal control zones) ^a	Sartain <i>et al.</i> 2015 ^a
<i>Ludwigia peploides</i> – Creeping water primrose	Onagraceae	19	Chemical barrier (herbicidal control zones) ^{a,b}	Richardson <i>et al.</i> 2008 ^a ; Saunders and Pezeshki 2014 ^b
<i>Baccharis halimifolia</i> – Groundsel tree	Asteraceae	17	<u>Physiological barrier (alteration of hydrodynamic regime)</u>	Caño <i>et al.</i> 2013; Frau <i>et al.</i> 2014 ^a
<i>Solidago canadensis</i> – Goldenrod	Asteraceae	17	<u>Physiological barrier (alteration of light intensities)</u>	Sun <i>et al.</i> 2008 ^a
<i>Impatiens glandulifera</i> – Himalayan balsam	Balsaminaceae	9	<u>Physiological barrier (alteration of hydrology – flooding events^a; changes in water temperature^b)</u>	Tickner <i>et al.</i> 2001 ^a ; Willis and Hulme 2002 ^b
<i>Myriophyllum aquaticum</i> – Parrot's feather	Haloragaceae	6	<u>Physiological barrier (changes in water temperature)^a</u>	Anderson <i>et al.</i> 2015 ^a
<i>Lysichiton americanus</i> – American skunk cabbage	Araceae			Schrader <i>et al.</i> 2010
• Animalia				
○ Mollusca				
<i>Dreissena polymorpha</i> – Zebra mussel	Dreissenidae	23	<u>Physical barrier (filtering, flow velocity)^a; Physiological barrier (increased water temperature)^b</u> ; Chemical barrier (control zones (three molluscicides)) ^c	Bodamer and Bossenbroek 2008 ^a ; Anderson <i>et al.</i> 2015 ^b ; Lund <i>et al.</i> 2018 ^c
<i>Pomacea canaliculata</i> – Golden apple snail	Ampullariidae	20	Chemical barrier (molluscicide control zones) ^a ; <u>Physiological barrier (changes in water temperature^{b,c}; lower pH, salinity^d)</u>	Wada 2004 ^a ; Matsukura <i>et al.</i> 2009 ^b ; Yoshida <i>et al.</i> 2014 ^c ; Bernatis <i>et al.</i> 2016 ^d
<i>Potamopyrgus antipodarum</i> – New Zealand mud snail	Hydrobiidae	19	<u>Physiological barrier (different temperatures^a; changes in endocrinology^c; increased CO₂ concentrations^d)</u> ; Chemical barrier (molluscicide control zones) ^b	Richards <i>et al.</i> 2004 ^a ; Gust <i>et al.</i> 2009 ^b ; Gust <i>et al.</i> 2010 ^c ; Treanor <i>et al.</i> 2017 ^d

<i>Pomacea maculata</i> – Island applesnail	Ampullariidae	17	Physiological barrier (lower water temperature^a; lower pH, salinity^b)	Yoshida <i>et al.</i> 2014 ^a ; Bernatis <i>et al.</i> 2016 ^b
<i>Marisa cornuarietis</i> – Colombian ramshorn apple snail	Ampullariidae	14	Physiological barrier (lower water temperature^a); Chemical barrier (molluscicide control zones)^b	Selck <i>et al.</i> 2006 ^a ; Forbes <i>et al.</i> 2008 ^b
<i>Corbicula fluminea</i> – Asiatic clam	Corbiculidae	10	Chemical barrier (control zones of halogens)^a; Physiological barrier (gas impermeable benthic barriers to reduce dissolved oxygen (DO) concentrations^b; increased CO₂ concentrations^c)	Doherty <i>et al.</i> 1986 ^a ; Wittmann <i>et al.</i> 2012 ^b ; Treanor <i>et al.</i> 2017 ^c
○ Arthropoda				
▪ Crustacea				
<i>Dikerogammarus villosus</i> – Killer shrimp	Gammaridae	16	Physiological barrier (increased water temperature)^{a,c}; Physical barrier (height, flow velocity)^b	Maazouzi <i>et al.</i> 2011 ^a ; Macneil and Platvoet 2013 ^b ; Anderson <i>et al.</i> 2015 ^c
<i>Procambarus clarkii</i> – Red swamp crayfish	Cambaridae	34	Physical barrier (height, flow velocity)^{a,b}	Kerby <i>et al.</i> 2005 ^a ; Frings <i>et al.</i> 2013 ^b
<i>Eriocheir sinensis</i> – Chinese mitten crab	Varunidae	28	Physiological barrier (changes in water temperature, salinity)^a; Physical barrier (height, flow velocity)^b	Anger 1991 ^a ; Frings <i>et al.</i> 2013 ^b
<i>Procambarus fallax</i> – Georgia crawfish	Cambaridae	28	Physical barrier (height, flow velocity)^a; Chemical barrier (pesticidal control zones)^b	Frings <i>et al.</i> 2013 ^a ; Koutnik <i>et al.</i> 2017 ^b
<i>Pacifastacus leniusculus</i> – Signal crayfish	Astacidae	19	Physiological barrier (zones of hyperoxia)^a; Physical barrier (height, flow velocity)^{b,c}	Wheatly 1989 ^a ; Bubb <i>et al.</i> 2005 ^b ; Frings <i>et al.</i> 2013 ^c
<i>Cherax quadricarinatus</i> – Redclaw crayfish	Parastacidae	18	Chemical barrier (pesticidal control zones)^a; Physical barrier (height, flow velocity)^b	Frontera <i>et al.</i> 2011 ^a ; Frings <i>et al.</i> 2013 ^b
<i>Cherax destructor</i> – Common yabby	Parastacidae	16	Physiological barrier (reduced water temperature)^a; Physical barrier (height, flow velocity)^b	Verhoef <i>et al.</i> 1998 ^a ; Frings <i>et al.</i> 2013 ^b
<i>Orconectes virilis</i> – Virile crayfish	Astacidae	15	Physiological barrier (reduced pH)^a; Physical barrier (height, flow velocity)^b	France 1993 ^a ; Frings <i>et al.</i> 2013 ^b
<i>Orconectes limosus</i> – Spinycheek crayfish	Astacidae	8	Physical barrier (height, flow velocity)^a; Sensory barrier (electrical current)^b	Frings <i>et al.</i> 2013 ^a ; Benejam <i>et al.</i> 2015 ^b
○ Chordata				
▪ Fish				
<i>Carassius auratus</i> – Goldfish	Cyprinidae	24	Sensory barrier (olfactory)^a; Physical barrier (height, jumping capacity)^b	Sorensen and Stacey 2004 ^a ; Morán-López and Tolosa 2017 ^b
<i>Oreochromis mossambicus</i> – Mozambique tilapia	Cichlidae	21	Sensory barrier (olfactory)^a; Physical barrier (swimming capacity)^b	Sorensen and Stacey 2004 ^a ; Starrs <i>et al.</i> 2017 ^b
<i>Oreochromis niloticus</i> – Nile tilapia	Cichlidae	18	Sensory barrier (olfactory)^a; Physical barrier (height, flow velocity)^b; Physiological barrier (increased CO₂ concentrations)^c	Sorensen and Stacey 2004 ^a ; Zambrano <i>et al.</i> 2006 ^b ; Treanor <i>et al.</i> 2017 ^c

<i>Pseudorasbora parva</i> – Topmouth gudgeon	Cyprinidae	17	<u>Sensory barrier (olfactory)^a; Physical barrier (height, flow velocity)^b</u>	Sorensen and Stacey 2004 ^a ; Chu <i>et al.</i> 2015 ^b
<i>Oncorhynchus mykiss</i> – Rainbow trout	Salmonidae	17	<u>Sensory barrier (olfactory)^a; Physiological barrier (increased CO₂ concentrations)^b; Physical barrier (swimming capacity)^c</u>	Sorensen and Stacey 2004 ^a ; Clingerman <i>et al.</i> 2007 ^b ; Starrs <i>et al.</i> 2017 ^c
<i>Micropterus dolomieu</i> – Smallmouth bass	Centrarchidae	16	<u>Sensory barrier (electrical)^a; Physiological barrier (reduced water temperature)^b</u>	Verrill and Berry 1995 ^a ; Landsman <i>et al.</i> 2011 ^b
<i>Ctenopharyngodon idella</i> – Grass carp	Cyprinidae	16	<u>Physical barrier (height, flow velocity)^a</u>	Maceina <i>et al.</i> 1999 ^a
<i>Poecilia reticulata</i> – Guppy	Poeciliidae	13	Chemical barrier (pesticidal control zones (atrazine)) ^a	Araújo <i>et al.</i> 2018 ^a
<i>Gambusia holbrooki</i> – Eastern mosquitofish	Poeciliidae	11	Chemical barrier (pesticidal control zones) ^a ; <u>Physical barrier (swimming capacity)^b; Physiological barrier (increased CO₂ concentrations)^c</u>	Willis and Ling 2000 ^a ; Starrs <i>et al.</i> 2017 ^b ; Treanor <i>et al.</i> 2017 ^c
<i>Phoxinus phoxinus</i> – Eurasian minnow	Cyprinidae		Sensory barrier (olfactory) ^a ; <u>Physical barrier (height, jumping capacity, flow velocity)^{b,c}</u>	Sorensen and Stacey 2004 ^a ; Holthe <i>et al.</i> 2005 ^b ; Kukuła <i>et al.</i> 2006 ^c
<i>Cyprinus carpio</i> – Common carp	Cyprinidae		<u>Sensory barrier (electrical^{a,c,d}; olfactory^b); Physical barrier (height, jumping capacity^e; body morphology (bar grates)^f); Physiological barrier (increased CO₂ concentrations)^{g,h}</u>	Verrill and Berry 1995 ^a ; Sorensen and Stacey 2004 ^b ; Dettmers <i>et al.</i> 2005 ^c ; Parker <i>et al.</i> 2015 ^d ; Holthe <i>et al.</i> 2005 ^e ; Hillyard <i>et al.</i> 2010 ^f ; Donaldson <i>et al.</i> 2016 ^g ; Treanor <i>et al.</i> 2017 ^h
▪ Amphibia				
<i>Lithobates catesbeianus</i> – American bullfrog	Ranidae	18	<u>Physical / physiological barrier (managing waterbodies to limit reproduction)^a; Physiological barrier (increased CO₂ concentrations)^b</u>	Madalozzo <i>et al.</i> 2016 ^a ; Treanor <i>et al.</i> 2017 ^b
<i>Xenopus laevis</i> – African clawed frog	Pipidae	15	<u>Physical barrier (height, increased flow velocity and discharge)^a; Chemical barrier (insecticidal control zones)^b; Physiological barrier (increased CO₂ concentrations)^c</u>	Lobos <i>et al.</i> 2013 ^a ; Yu <i>et al.</i> 2013 ^b ; Treanor <i>et al.</i> 2017 ^c

The current extent of IAS management with barriers is quite crude because most existing barriers to IAS also impact a variety of native species. In the future, as selective passage techniques evolve, effectiveness of management programmes for freshwater invasive species will be more dependent on supporting selective passage, so that desirable, endemic species are left unhindered in their movement, while at the same time unwanted, invasive biota are blocked from colonising areas upstream or downstream. Based on this concept, examples of management strategies of an invasive species indicative of each taxonomic group are discussed in the next section.

Floating pennywort (*Hydrocotyle ranunculoides*) is native to North America and was naturalized in South and Central America, but it is considered invasive in western Europe. Its main habitat is stagnant or lentic waters such as canals, lakes and ponds, where it can quickly grow to form dense interwoven mats under the right environmental conditions (sunlight and high nutrient availability), thereby blocking sunlight into the water column. Since physical barriers cause impounded zones upstream, settlement of invasive species such as *H. ranunculoides* may be facilitated through unintentional transfer of propagules (Hoeinghaus *et al.* 2009; Casimiro *et al.* 2017). Hussner and Meyer (2009) investigated the response by floating pennywort at three different water levels, and found that growth rate and chlorophyll content was hindered by drained and semi-drained conditions compared to waterlogged habitat. Changes in the hydrologic regime by closely managing operating regimes of sluices and levees, or (temporarily) altering existing physical structures so a different hydrologic regime can be achieved in reaches invaded by floating pennywort may thus be beneficial in controlling its spread (*Table 1*).

The crustacean *Pacifastacus leniusculus*, also known as signal crayfish, is endemic to western North America but, since the 1960's, has been introduced to over 20 countries in Europe. It has caused, and is causing, further declines of European crayfish species by their continued spread within and between catchments (Bubb *et al.* 2005; Ruokonen *et al.* 2018). Physical barriers have been used as a management strategy to control the spread of signal crayfish (*Table 1*). Frings *et al.* (2013) studied the effectiveness of physical barriers to block passage of *P. leniusculus*, while still allowing passage of fish species, and concluded that physical crayfish barriers can be successful in protecting native crayfish at obstacles / passage devices with sufficiently high flow velocities and gradients. Weirs and substantial natural waterfalls may also prevent upstream colonisation by undesired crayfish species, as argued by Bubb *et al.* (2005). In catchments where signal crayfish have been encountered, modifications to existing barriers to increase flow velocities and gradients may limit the spread of this invasive. Such restoration efforts should be undertaken with careful

consideration of endemic biota in the invaded river system, so as not to impede on their free movement.

The African clawed frog *Xenopus laevis* originates from sub-Saharan Africa and is a successful amphibian invader which has spread across many major areas globally. Although dispersed widely, it has not been perceived as a species that causes impacts on biodiversity, but has been acknowledged as a vector for a fungus which may cause amphibian decline (Pounds *et al.* 2006). While techniques aimed at controlling the spread of the African clawed frog exist including draining wetland habitats to remove habitat essential for reproduction (Maret *et al.* 2006), they are often ineffective or unfeasible (Snow and Witmer 2010). They may have severe negative effects on non-target species, as reported by Yu *et al.* (2013) for insecticides which caused mortality, malformations and growth impairments for not only *X. laevis*, but for other, endemic amphibians as well. An emerging management approach is using physiological barriers of elevated CO₂ concentrations in the water column (*Table 1*), which has been reported to cause 100% mortality of *X. laevis* tadpoles at sufficiently high CO₂ concentrations (Treanor *et al.* 2017). An adaptive barrier management approach may be developed, such as a GIS framework to evaluate the distribution of physical barriers in the invaded catchment in combination with using barrier network algorithms to simulate fragmentation metrics (King and O'Hanley 2016). At sites where physical barriers are present, and where the invasion front has established, barriers may be modified to enable infusion of CO₂ into the water column. The combination of types of barriers acting on different biological traits of this invasive species (the in-stream physical barrier plus the physiological barrier) may prove successful in stopping their spread.

Eurasian minnow is a small-bodied cyprinid and considered invasive in some parts of Europe, principally parts of Scandinavia. Areas in which benthic macroinvertebrate diversity has declined and a marked increase in small zoobenthos recorded (Borgstrøm *et al.* 1996). Indigenous fishes of temperate river systems such as salmonids share food and habitat niche-space with European minnow, and interspecific competition may thus be prevalent (Museth *et al.* 2010). Endemic fish species such as brown trout *Salmo trutta* have become impacted in their recruitment, yield and fitness as a result of minnow expansion across waterways (Museth *et al.* 2007). By using artificial barriers, the often undesired Eurasian minnow can be selectively prevented from reaching upstream reaches based on their limited jumping capacity (*Table 1*), while still allowing salmonids such as brown trout to pass, which possess a stronger capacity to jump. Holthe *et al.* (2005) showed that further unwanted dispersal of the minnow was prevented by constructing suitable waterfall barriers,

while brown trout were still able to pass the barrier. The effect was temperature-dependent; for a water temperature of 4.9 - 6.5 °C no successful leap of minnows was recorded even for a barrier of only 3 cm high, while brown trout leaped over barriers up to 40 cm in height. At 14.0 - 16.5 °C, minnows were able to negotiate waterfall barriers up to 27 cm high. By making use of barriers in an identical approach, it may thus be possible to allow for selective passage of desired species while limiting the spread of undesired fishes based on their capacity to overcome vertical barriers.

6. Conclusion

Finding the right balance between protecting and conserving freshwater biodiversity on the one hand and allowing unhindered movement up- and downstream of endemic species while minimising that of invasive species on the other is crucial for effective management of waterways. Methods of selective passage are likely to become increasingly important to protect aquatic species richness (Silva *et al.* 2018), and the focus in water management is gradually changing from purely maximizing the biomass of economically important species (Rahel and McLaughlin 2018). Impacts of invasive species in river systems are dependent on characteristics of the invader and of the invaded ecosystem (Ricciardi and Atkinson 2004), and can manifest across multiple trophic levels (Maggi *et al.* 2015). Value of conservation of naturally occurring aquatic species in the system should therefore be analysed on a case-by-case basis, with utmost consideration of the detrimental effect of invasive species if their spread is not blocked or limited by the use of in-stream barriers, be it physical, physiological, sensory or chemical. Accordingly when carrying out, or updating, River Basin Management Plans under the Water Framework Directive, all European freshwater catchment managers should consider threats from AIS and the potential (or otherwise) for barriers to facilitate their control as part of an Adaptive Management framework.

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8. References

- Alonso, A., Castro-Diez, P. (2008). What explains the invading success of the aquatic mud snail *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca)? *Hydrobiologia* **614**: 107-116.
- Anderson, L. G., Dunn, A. M., Rosewarne, P. J., Stebbing, P. D. (2015). Invaders in hot water: a simple decontamination method to prevent the accidental spread of aquatic invasive non-native species. *Biological Invasions* **17**: 2287-2297.
- Anger, K. (1991). Effects of temperature and salinity on the larval development of the Chinese mitten crab *Eriocheir sinensis* (Decapoda: Grapsidae). *Marine Ecology Progress Series*. **72**: 103-110.
- Araújo, C. V., Silva, D. C., Gomes, L. E., Acayaba, R. D., Montagner, C. C., Moreira-Santos, M., Pompêo, M. L. (2018). Habitat fragmentation caused by contaminants: atrazine as a chemical barrier isolating fish populations. *Chemosphere* **193**: 24-31.
- Bae, M. J., Murphy, C. A., García-Berthou, E. (2018). Temperature and hydrologic alteration predict the spread of invasive Largemouth Bass (*Micropterus salmoides*). *Science of the Total Environment* **639**: 58-66.
- Bajer, P. G., Claus, A. C., Wein, J., Kukulski, E. (2018). Field test of a low-voltage, portable electric barrier to guide invasive common carp into a mock trap during seasonal migrations. *Management of Biological Invasions* **9**: 291-297.
- Bajer, P. G., Cross, T. K., Lechelt, J. D., Chizinski, C. J., Weber, M. J., Sorensen, P. W. (2015). Across-ecoregion analysis suggests a hierarchy of ecological filters that regulate recruitment of a globally invasive fish. *Diversity and Distributions* **21**: 500-510.
- Bashtanova, U. B., Beckett, K. P., and Flowers, T. J. (2009). Physiological approaches to the improvement of chemical control of Japanese knotweed (*Fallopia japonica*). *Weed Science* **57**: 584-592.
- Baudoin, J. M., Burgun, V., Chanseau, M., Larinier, M., Ovidio, M., Sremski, W., Voegtli, B. (2015). *Assessing the passage of obstacles by fish. Concepts, design and application* (ed. V. Barre). Onema, Paris, France. 200 pp.
- Baxter-Gilbert, J. H., Riley, J. L., Lesbarrères, D., Litzgus, J. D. (2015). Mitigating reptile road mortality: fence failures compromise ecopassage effectiveness. *PLoS One* **10**: e0120537.
- Benejam, L., Saura-Mas, S., Montserrat, J., Torres, F., Macies, M. (2015). Could electric fish barriers help to manage native populations of European crayfish threatened by crayfish plague (*Aphanomyces astaci*)? *Management* **6**: 307-310.
- Bernatis, J. L., Mcgaw, I. J., Cross, C. L. (2016). Abiotic tolerances in different life stages of apple snails *Pomacea canaliculata* and *Pomacea maculata* and the implications for distribution. *Journal of Shellfish Research* **35**: 1013-1026.
- Birnie-Gauvin, K., Tummers, J. S., Lucas, M. C., Aarestrup, K. (2017). Adaptive management in the context of barriers in European freshwater ecosystems. *Journal of Environmental Management* **204**: 436-441.
- Bodamer, B. L., Bossenbroek, J. M. (2008). Wetlands as barriers: effects of vegetated waterways on downstream dispersal of zebra mussels. *Freshwater Biology* **53**: 2051-2060.
- Borgstrøm, R., Brittain, J. E., Hasle, K., Skjølås, S., Dokk, J. G. (1996) Reduced recruitment in brown trout *Salmo trutta*, the role of interactions with the minnow *Phoxinus phoxinus*. *Nordic Journal of Freshwater Research* **72**: 30-38.
- Boulétreau, S., Gaillagot, A., Carry, L., Tétard, S., De Oliveira, E., Santoul, F. (2018). Adult Atlantic salmon have a new freshwater predator. *PLoS One* **13**: e0196046.
- Brodie, J. F., Giordano, A. J., Dickson, B., Hebblewhite, M., Bernard, H., Mohd-Azlan, J., Ambu, L. (2015). Evaluating multispecies landscape connectivity in a threatened tropical mammal community. *Conservation Biology* **29**: 122-132.
- Bubb, D. H., Thom, T. J., Lucas, M. C. (2005). The within-catchment invasion of the non-indigenous signal crayfish *Pacifastacus leniusculus* (Dana), in upland rivers. *Bulletin Français de la Pêche et de la Pisciculture* **376-377**: 665-673.
- Caffrey, J. M., Madsen, J. D. (2001). The management of giant hogweed in an Irish river catchment. *Journal of Aquatic Plant Management* **39**: 28-33.

- Caño, L., Campos, J. A., García-Magro, D., Herrera, M. (2013). Replacement of estuarine communities by an exotic shrub: distribution and invasion history of *Baccharis halimifolia* in Europe. *Biological Invasions* **15**: 1183-1188.
- Caraco, N. F., Cole, J. J., Raymond, P. A., Strayer, D. L., Pace, M. L., Findlay, S. E., Fischer, D. T. (1997). Zebra mussel invasion in a large, turbid river: phytoplankton response to increased grazing. *Ecology* **78**: 588-602.
- Carman, S. M., Janssen, J., Jude, D. J., Berg, M. B. (2006). Diel interactions between prey behaviour and feeding in an invasive fish, the round goby, in a North American river. *Freshwater Biology* **51**: 742-755.
- Casimiro, A. C. R., Garcia, D. A. Z., Costa, A. D. A., Britton, J. R., Orsi, M. L. (2017). Impoundments facilitate a biological invasion: dispersal and establishment of non-native armoured catfish *Loricariichthys platymetopon* (Isbrückler and Nijssen, 1979) in a Neotropical river. *Limnologia-Ecology and Management of Inland Waters* **62**: 34-37.
- Chapman, L. J., McKenzie, D. J. (2009). Behavioral responses and ecological consequences. In: Richards, J. G., Farrell, A. P., Brauner, C. J. (eds) *Hypoxia*. Elsevier, London, pp 25-77.
- Charles, H., Dukes, J. S. (2008). Impacts of invasive species on ecosystem services. In *Biological Invasions*. Springer, Berlin, Germany. pp 217-237.
- Charlton, P. E., Gurney, M., Lyons, G. (2010). Largescale eradication of New Zealand pygmyweed *Crassula helmsii* from grazing marsh by inundation with seawater, Old Hall Marshes RSPB reserve, Essex, England. *Conservation Evidence* **7**: 130-133.
- Chu, L., Wang, W., Zhu, R., Yan, Y., Chen, Y., Wang, L. (2015). Variation in fish assemblages across impoundments of low-head dams in headwater streams of the Qingyi River, China: effects of abiotic factors and native invaders. *Environmental Biology of Fishes* **98**: 101-112.
- Clarkson, R. W., Marsh, P. C., Dowling, T. E. (2012). Population prioritization for conservation of imperilled warmwater fishes in an arid-region drainage. *Aquatic Conservation: Marine and Freshwater Ecosystems* **22**: 498-510.
- Clay, C. H. 1995. Design of Fishways and Other Fish Facilities. (2nd ed.), Lewis Publishers, Boca Raton, LA, USA. 248 pp.
- Clingerman, J., Bebak, J., Mazik, P. M., Summerfelt, S. T. (2007). Use of avoidance response by rainbow trout to carbon dioxide for fish self-transfer between tanks. *Aquacultural Engineering* **37**: 234-251.
- Coulter, D. P., MacNamara, R., Glover, D. C., Garvey, J. E. (2018). Possible unintended effects of management at an invasion front: Reduced prevalence corresponds with high condition of invasive bigheaded carps. *Biological Conservation* **221**: 118-126.
- Cupp, A., Smerud, J., Tix, J., Schleis, S., Fredricks, K., Erickson, R., Amberg, J., Morrow, W., Koebel, C., Murphy, E., Vishy, C., Blodgett, D. (2018). Field evaluation of carbon dioxide as a fish deterrent at a water management structure along the Illinois River. *Management of Biological Invasions* **9**: 299-308.
- Dana, E. D., García-de-Lomas, J., González, R., Ortega, F. (2011). Effectiveness of dam construction to contain the invasive crayfish *Procambarus clarkii* in a Mediterranean mountain stream. *Ecological Engineering* **37**: 1607-1613.
- Daniel, A. J., Morgan, D. K., Ling, N. (2014). Get out, stay out! Restoring a small New Zealand floodplain lake: removal and exclusion of carp. In *Carp management in Australia-state of knowledge*. Invasive Animals Cooperative Research Centre. pp. 132-139.
- Darrigran, G., Damborenea, C. (2011). Ecosystem engineering impact of *Limnoperna fortunei* in South America. *Zoological Science* **28**: 1-7.
- DeFries, R., Hansen, A., Turner, B. L., Reid, R., Liu, J. (2007). Land use change around protected areas: management to balance human needs and ecological function. *Ecological Applications* **17**: 1031-1038.
- Dettmers, J. M., Boisvert, B. A., Barkley, T., Sparks, R. E. (2005). *Potential impact of steel-hulled barges on movement of fish across an electric barrier to prevent the entry of invasive carp into Lake Michigan*. INHS Center for Aquatic Ecology. University of Illinois, USA. 20 pp.
- Didham, R. K. (2017). Ecological consequences of habitat fragmentation. A21904. In *Encyclopedia of Life Sciences (ELS)*, Wiley, London, UK. 39 pp.
- Doherty, F. G., Farris, J. L., Cherry, D. S., Cairns, J. (1986). Control of the freshwater fouling bivalve *Corbicula fluminea* by halogenation. *Archives of Environmental Contamination and Toxicology* **15**: 535-542.

- Domenici, P., Herbert, N. A., Lefrançois, C., Steffensen, J. F., McKenzie, D. J. (2013). The effect of hypoxia on fish swimming performance and behaviour. In: *Swimming Physiology of Fish*. Springer, Berlin, Germany. pp 129-159.
- Donaldson, M. R., Amberg, J., Adhikari, S., Cupp, A., Jensen, N., Romine, J., Suski, C. D. (2016). Carbon dioxide as a tool to deter the movement of invasive bigheaded carps. *Transactions of the American Fisheries Society* **145**: 657-670.
- Donnelly, M. J., Walters, L. J. (2008). Water and boating activity as dispersal vectors for *Schinus terebinthifolius* (Brazilian pepper) seeds in freshwater and estuarine habitats. *Estuaries and Coasts* **31**: 960.
- Drouineau, H., Carter, C., Rambonilaza, M., Beaufaron, G., Bouleau, G., Gassiat, A., de Oliveira, E. (2018). River continuity restoration and diadromous fishes: much more than an ecological issue. *Environmental Management* **61**: 671-686.
- Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., Sullivan, C. A. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological Reviews* **81**: 163-182.
- Fausch, K. D., Rieman, B. E., Dunham, J. B., Young, M. K., Peterson, D. P. (2009). Invasion versus isolation: trade-offs in managing native salmonids with barriers to upstream movement. *Conservation Biology* **23**: 859-870.
- Ficetola, G., Coïc, C., Detaint, M., Berroneau, M., Lorvelec, O., Miaud, C. (2006). Pattern of distribution of the American bullfrog *Rana catesbeiana* in Europe. *Biological Invasions* **9**: 767-772.
- Ficke, A. D., Myrick, C. A., Jud, N. (2011). The swimming and jumping ability of three small Great Plains fishes: implications for fishway design. *Transactions of the American Fisheries Society* **140**: 1521-1531.
- Figuerola, J., Green, A. J., Santamaría, L. (2003). Passive internal transport of aquatic organisms by waterfowl in Doñana, south-west Spain. *Global Ecology and Biogeography* **12**: 427-436.
- Forbes, V. E., Warbritton, R., Aufderheide, J., Van Der Hoeven, N., Caspers, N. (2008). Effects of bisphenol A on fecundity, egg hatchability, and juvenile growth of *Marisa cornuarietis*. *Environmental Toxicology and Chemistry* **27**: 2332-2340.
- France, R. L. 1993. Influence of lake pH on the distribution, abundance and health of crayfish in Canadian Shield lakes. *Hydrobiologia* **271**: 65-70.
- Frau, D., Ondiviela Eizaguirre, B., Galván Arbeiza, C., Juanes de la Peña, J. A. (2014). The role of the hydrodynamic regime in the distribution of the invasive shrub *Baccharis halimifolia* (Compositae) in Oyambre Estuary (Cantabria, Spain). *Limnetica* **33**: 1-12.
- Frick, K. E., Corbett, S. C., Moser, M. L. (2017). Climbing success of adult Pacific lamprey on a vertical wetted wall. *Fisheries Management and Ecology* **24**: 230-239.
- Frings, R. M., Vaeßen, S. C., Groß, H., Roger, S., Schüttrumpf, H., Hollert, H. (2013). A fish-passable barrier to stop the invasion of non-indigenous crayfish. *Biological Conservation* **159**: 521-529.
- Frontera, J. L., Vatnick, I., Chaulet, A., Rodríguez, E. M. (2011). Effects of glyphosate and polyoxyethylenamine on growth and energetic reserves in the freshwater crayfish *Cherax quadricarinatus* (Decapoda, Parastacidae). *Archives of Environmental Contamination and Toxicology* **61**: 590-598.
- Fullerton, A. H., Burnett, K. M., Steel, E. A., Flitcroft, R. L., Pess, G. R., Feist, B. E., Sanderson, B. L. (2010). Hydrological connectivity for riverine fish: measurement challenges and research opportunities. *Freshwater Biology* **55**: 2215-2237.
- Gallardo, B., Clavero, M., Sánchez, M. I., Vilà, M. (2016). Global ecological impacts of invasive species in aquatic ecosystems. *Global Change Biology* **22**: 151-163.
- Galpern, P., Manseau, M., Fall, A. (2011). Patch-based graphs of landscape connectivity: a guide to construction, analysis and application for conservation. *Biological Conservation* **144**: 44-55.
- Gardiner, T., Charlton, P. (2012). Effects of seawater flooding on Orthoptera and the yellow meadow ant *Lasius flavus* during New Zealand pygmy weed *Crassula helmsii* eradication at Old Hall Marshes, Essex, England. *Conservation Evidence* **9**: 50-53.
- Giachalone, G., Valvo, M. L., Faraone, F. P., Lillo, F. (2008). The large invasive population of *Xenopus laevis* in Sicily, Italy. *Amphibia-Reptilia* **29**: 405-412.

- Gibbs, M. A., Northcutt, R. G. (2004). Development of the lateral line system in the shovelnose sturgeon. *Brain, Behavior and Evolution* **64**: 70-84.
- Gobel, N., Laufer, G., Cortizas, S. (2019). Changes in aquatic communities recently invaded by a top predator: evidence of American bullfrogs in Aceguá, Uruguay. *Aquatic Sciences* **81**: 1-11.
- Goodman, D. H., Reid, S. B. (2017). Climbing above the competition: Innovative approaches and recommendations for improving Pacific Lamprey passage at fishways. *Ecological Engineering* **107**: 224-232.
- Guderley, H., Pörtner, H. O. (2010). Metabolic power budgeting and adaptive strategies in zoology: examples from scallops and fish. *Canadian Journal of Zoology* **88**: 753-763.
- Gust, M., Buronfosse, T., Giamberini, L., Ramil, M., Mons, R., Garric, J. (2009). Effects of fluoxetine on the reproduction of two prosobranch mollusks: *Potamopyrgus antipodarum* and *Valvata piscinalis*. *Environmental Pollution* **157**: 423-429.
- Gust, M., Garric, J., Giamberini, L., Mons, R., Abbaci, K., Garnier, F., Buronfosse, T. (2010). Sensitivity of New Zealand mudsnail *Potamopyrgus antipodarum* (Gray) to a specific aromatase inhibitor. *Chemosphere* **79**: 47-53.
- Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., Cook, W. M. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances* **1**: e1500052.
- Hagman, M., Shine, R. (2009). Larval alarm pheromones as a potential control for invasive cane toads (*Bufo marinus*) in tropical Australia. *Chemoecology* **19**: 211-217.
- Hall, C. J., Jordaan, A., Frisk, M. G. (2011). The historic influence of dams on diadromous fish habitat with a focus on river herring and hydrologic longitudinal connectivity. *Landscape Ecology* **26**: 95-107.
- Hannan, K. D., Jeffrey, J. D., Hasler, C. T., Suski, C. D. (2016). Physiological effects of short-and long-term exposure to elevated carbon dioxide on a freshwater mussel, *Fusconaia flava*. *Canadian Journal of Fisheries and Aquatic Sciences* **73**: 1538-1546.
- Heath, M. R., Speirs, D. C., Steele, J. H. (2014). Understanding patterns and processes in models of trophic cascades. *Ecology Letters* **17**: 101-114.
- Hellmann, J. J., Byers, J. E., Bierwagen, B. G., Dukes, J. S. (2008). Five potential consequences of climate change for invasive species. *Conservation Biology* **22**: 534-543.
- Hesselschwerdt, J., Wantzen, K. M. (2018). Global warming may lower thermal barriers against invasive species in freshwater ecosystems - A study from Lake Constance. *Science of the Total Environment* **645**: 44-50.
- Hillyard, K. A., Smith, B. B., Conallin, A. J., Gillanders, B. M. (2010). Optimising exclusion screens to control exotic carp in an Australian lowland river. *Marine and Freshwater Research* **61**: 418-429.
- Hoeinghaus, D. J., Agostinho, A. A., Gomes, L. C., Pelicice, F. M., Okada, E. K., Latini, J. D., Winemiller, K. O. (2009). Effects of river impoundment on ecosystem services of large tropical rivers: embodied energy and market value of artisanal fisheries. *Conservation Biology* **23**: 1222-1231.
- Holthe, E., Lund, E., Finstad, B., Thorstad, E. B., McKinley, R. S. (2005). A fish selective obstacle to prevent dispersion of an unwanted fish species, based on leaping capabilities. *Fisheries Management and Ecology* **12**: 143-147.
- Hoyer, S. A., Myrick, C. A. (2012). Can copper-based substrates be used to protect hatcheries from invasion by the New Zealand mudsnail? *North American Journal of Aquaculture* **74**: 575-583.
- Hume, J. B., Meckley, T. D., Johnson, N. S., Luhring, T. M., Siefkes, M. J., Wagner, C. M. (2015). Application of a putative alarm cue hastens the arrival of invasive sea lamprey (*Petromyzon marinus*) at a trapping location. *Canadian Journal of Fisheries and Aquatic Sciences* **72**: 1799-1806.
- Hussner, A., Meyer, C. (2009). The influence of water level on the growth and photosynthesis of *Hydrocotyle ranunculoides* L. fil. *Flora-Morphology, Distribution, Functional Ecology of Plants* **204**: 755-761.

- Hussner, A., Stiers, I., Verhofstad, M. J. J. M., Bakker, E. S., Grutters, B. M. C., Haury, J., Anderson, L. W. J. (2017). Management and control methods of invasive alien freshwater aquatic plants: a review. *Aquatic Botany* **136**: 112-137.
- Jager, H. I., Parsley, M. J., Cech Jr, J. J., McLaughlin, R. L., Forsythe, P. S., Elliott, R. F., Pracheil, B. M. (2016). Reconnecting fragmented sturgeon populations in North American rivers. *Fisheries* **41**: 140-148.
- Jensen, A. J., Jones, M. L. (2017). Forecasting the response of Great Lakes sea lamprey (*Petromyzon marinus*) to barrier removals. *Canadian Journal of Fisheries and Aquatic Sciences* **75**: 1415-1426.
- Johnson, N. S., Miehl, S., O'Connor, L. M., Bravener, G., Barber, J., Thompson, H., Bruning, T. (2016). A portable trap with electric lead catches up to 75% of an invasive fish species. *Scientific Reports* **6**: 28430.
- Johnson, P. T., Olden, J. D., Solomon, C. T., Van der Zanden, M. J. (2009). Interactions among invaders: community and ecosystem effects of multiple invasive species in an experimental aquatic system. *Oecologia* **159**: 161-170.
- Jongman, R. H., Külvik, M., Kristiansen, I. (2004). European ecological networks and greenways. *Landscape and Urban Planning* **68**: 305-319.
- Kappes, H., Haase, P. (2012). Slow, but steady: dispersal of freshwater molluscs. *Aquatic Sciences* **74**: 1-14.
- Kates, D., Dennis, C., Noatch, M. R., Suski, C. D. (2012). Responses of native and invasive fishes to carbon dioxide: potential for a nonphysical barrier to fish dispersal. *Canadian Journal of Fisheries and Aquatic Sciences* **69**: 1748-1759.
- Keller, R. P., Drake, J. M., Drew, M. B., Lodge, D. M. (2011). Linking environmental conditions and ship movements to estimate invasive species transport across the global shipping network. *Diversity and Distributions* **17**: 93-102.
- Kelly, N. E., Wantola, K., Weisz, E., Yan, N. D. (2013). Recreational boats as a vector of secondary spread for AIS and native crustacean zooplankton. *Biological Invasions* **15**: 509-519.
- Kennedy, T. A., Yackulic, C. B., Cross, W. F., Grams, P. E., Yard, M. D., Copp, A. J. (2014). The relation between invertebrate drift and two primary controls, discharge and benthic densities, in a large regulated river. *Freshwater Biology* **59**: 557-572.
- Kerby, J. L., Riley, S. P., Kats, L. B., and Wilson, P. (2005). Barriers and flow as limiting factors in the spread of an invasive crayfish (*Procambarus clarkii*) in southern California streams. *Biological Conservation* **126**: 402-409.
- Kernan, M. (2015). Climate change and the impact of invasive species on aquatic ecosystems. *Aquatic Ecosystem Health and Management* **18**: 321-333.
- Kieffer, J. D. (2010). Perspective - Exercise in fish: 50+ years and going strong. *Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology* **156**: 163-168.
- Kim, J., Mandrak, N. E. (2017). Effects of vertical electric barrier on the behaviour of common carp. *Management of Biological Invasions* **8**: 497-505.
- King, S., O'Hanley, J. R. (2016). Optimal fish passage barrier removal - revisited. *River Research and Applications* **32**: 418-428.
- Kirk, M. A., Caudill, C. C., Tonina, D., Syms, J. C. (2016). Effects of water velocity, turbulence and obstacle length on the swimming capabilities of adult Pacific lamprey. *Fisheries Management and Ecology* **23**: 356-366.
- Kitano, S. (2004). Ecological impacts of rainbow, brown and brook trout in Japanese inland waters. *Global Environmental Research - English Edition* **8**: 41-50.
- Koehn, J. D., MacKenzie, R. F. (2004). Priority management actions for alien freshwater fish species in Australia. *New Zealand Journal of Marine and Freshwater Research* **38**: 457-472.
- Koutnik, D., Stara, A., Zuskova, E., Kouba, A., Velisek, J. (2017). The chronic effects of terbuthylazine-2-hydroxy on early life stages of marbled crayfish (*Procambarus fallax f. virginalis*). *Pesticide Biochemistry and Physiology* **136**: 29-33.
- Kukuła, K. (2006). A low stone weir as a barrier for the fish in a mountain stream. *Polish Journal of Environmental Studies* **15**: 132-137.

- Landsman, S. J., Gingerich, A. J., Philipp, D. P., Suski, C. D. (2011). The effects of temperature change on the hatching success and larval survival of largemouth bass *Micropterus salmoides* and smallmouth bass *Micropterus dolomieu*. *Journal of Fish Biology* **78**: 1200-1212.
- Lechner, A., Keckeis, H., Schludermann, E., Humphries, P., McCasker, N., Tritthart, M. (2014). Hydraulic forces impact larval fish drift in the free flowing section of a large European river. *Ecohydrology* **7**: 648-658.
- Leuven, R. S., Van der Velde, G., Baijens, I., Snijders, J., Van der Zwart, C., Lenders, H. R., Bij de Vaate, A. (2009). The river Rhine: a global highway for dispersal of AIS. *Biological Invasions* **11**: 1989-2008.
- Liew, J. H., Tan, H. H., Yeo, D. C. (2016). Dammed rivers: impoundments facilitate fish invasions. *Freshwater Biology* **61**: 1421-1429.
- Linares, M. S., Callisto, M., Marques, J. C. (2018). Thermodynamic based indicators illustrate how a run-of-river impoundment in neotropical savanna attracts invasive species and alters the benthic macroinvertebrate assemblages' complexity. *Ecological Indicators* **88**: 181-189.
- Liu, F., Wang, J., Cao, W. (2012). Long-term changes in fish assemblage following the impoundments of the Three Gorges Reservoir in Hejiang, a protected reach of the upper Yangtze River. *Knowledge and Management of Aquatic Ecosystems* **407**: 06.
- Liu, X., Wang, H. (2018). Effects of loss of lateral hydrological connectivity on fish functional diversity. *Conservation Biology* **32**: 1336-1345.
- Lobos, G., Cattán, P., Estades, C., Jaksic, F. M. (2013). Invasive African clawed frog *Xenopus laevis* in southern South America: key factors and predictions. *Studies on Neotropical Fauna and Environment* **48**: 1-12.
- Lodge, D., Deines, A., Gherardi, F., Yeo, D., Arcella, T., Baldrige, A., Barnes, M., Chadderton, W., Feder, J., Gantz, C., Howard, G., Jerde, C., Peters, B., Peters, J., Sargent, L., Turner, C., Wittmann, M. Zeng, Y. (2012). Global introductions of crayfishes: evaluating the impact of species invasions on ecosystem services. *Annual Review of Ecology, Evolution, and Systematics* **43**: 449-472.
- Louette, G., Devisscher, S., Adriaens, T. (2013). Control of invasive American bullfrog *Lithobates catesbeianus* in small shallow water bodies. *European Journal of Wildlife Research* **59**: 105-114.
- Lovell, S. J., Stone, S. F., Fernandez, L. (2006). The economic impacts of AIS: a review of the literature. *Agricultural and Resource Economics Review* **35**: 195-208.
- Lucas, M. C., Baras, E. (2001). *Migration of Freshwater Fishes*. Blackwell Science, Oxford, UK. 440 pp.
- Lund, K., Cattoor, K. B., Fieldseth, E., Sweet, J., McCartney, M. A. (2018). Zebra mussel (*Dreissena polymorpha*) eradication efforts in Christmas Lake, Minnesota. *Lake and Reservoir Management* **34**: 7-20.
- Maazouzi, C., Piscart, C., Legier, F., Hervant, F. (2011). Ecophysiological responses to temperature of the "killer shrimp" *Dikerogammarus villosus*: is the invader really stronger than the native *Gammarus pulex*? *Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology* **159**: 268-274.
- Maceina, M. J., Slipke, J. W., Grizzle, J. M. (1999). Effectiveness of three barrier types for confining grass carp in embayments of Lake Seminole, Georgia. *North American Journal of Fisheries Management* **19**: 968-976.
- Macneil, C., Platvoet, D. (2013). Could artificial structures such as fish passes facilitate the establishment and spread of the 'killer shrimp' *Dikerogammarus villosus* (Crustacea: Amphipoda) in river systems? *Aquatic Conservation: Marine and Freshwater Ecosystems* **23**: 667-677.
- Madalozzo, B., Both, C., Cechin, S. (2016). Can protected areas with agricultural edges avoid invasions? The case of bullfrogs in the Southern Atlantic Rainforest in Brazil. *Zoological Studies* **55**: 1-13.
- Maggi, E., Benedetti-Cecchi, L., Castelli, A., Chatzinikolaou, E., Crowe, T. P., Ghedini, G., Rindi, L. (2015). Ecological impacts of invading seaweeds: a meta-analysis of their effects at different trophic levels. *Diversity and Distributions* **21**: 1-12.
- Magilligan, F. J., Graber, B. E., Nislow, K. H., Chipman, J. W., Sneddon, C. S., Fox, C. A. (2016). River restoration by dam removal: Enhancing connectivity at watershed scales. *Elementa: Science of the Anthropocene* **4**.
- Manea, A., Leishman, M. R. (2011). Competitive interactions between native and invasive exotic plant species are altered under elevated carbon dioxide. *Oecologia*, **165**: 735-744.

- Maret, T. J., Snyder, J. D., Collins, J. P. (2006). Altered drying regime controls distribution of endangered salamanders and introduced predators. *Biological Conservation* **127**: 129-138.
- Matsukura, K., Tsumuki, H., Izumi, Y., Wada, T. (2009). Physiological response to low temperature in the freshwater apple snail, *Pomacea canaliculata* (Gastropoda: Ampullariidae). *Journal of Experimental Biology* **212**: 2558-2563.
- McCracken, A., Bainard, J. D., Miller, M. C., Husband, B. C. (2013). Pathways of introduction of the invasive aquatic plant *Cabomba caroliniana*. *Ecology and Evolution* **3**: 1427-1439.
- McLaughlin, R. L., Smyth, E. R., Castro-Santos, T., Jones, M. L., Koops, M. A., Pratt, T. C., Vélez-Espino, L. A. (2013). Unintended consequences and trade-offs of fish passage. *Fish and Fisheries* **14**: 580-604.
- Meckley, T. D., Wagner, C. M., Gurarie, E. (2014). Coastal movements of migrating sea lamprey (*Petromyzon marinus*) in response to a partial pheromone added to river water: implications for management of invasive populations. *Canadian Journal of Fisheries and Aquatic Sciences* **71**: 533-544.
- Mercado-Silva, N., Helmus, M. R., Zanden, M. J. V. (2009). The effects of impoundment and non-native species on a river food web in Mexico's central plateau. *River Research and Applications* **25**: 1090-1108.
- Miehls, S. M., Johnson, N. S., Hrodey, P. J. (2017). Test of a nonphysical barrier consisting of light, sound, and bubble screen to block upstream movement of sea lampreys in an experimental raceway. *North American Journal of Fisheries Management* **37**: 660-666.
- Milt, A. W., Diebel, M. W., Doran, P. J., Ferris, M. C., Herbert, M., Khoury, M. L., O'Hanley, J. R. (2018). Minimizing opportunity costs to aquatic connectivity restoration while controlling an invasive species. *Conservation Biology* **32**: 894-904.
- Mims, M. C., Olden, J. D. (2013). Fish assemblages respond to altered flow regimes via ecological filtering of life history strategies. *Freshwater Biology* **58**: 50-62.
- Minor, E. S., Gardner, R. H. (2011). Landscape connectivity and seed dispersal characteristics inform the best management strategy for exotic plants. *Ecological Applications* **21**: 739-749.
- Moorhouse, T. P., Macdonald, D. W. (2015). Are invasives worse in freshwater than terrestrial ecosystems? *Wiley Interdisciplinary Reviews: Water* **2**: 1-8.
- Morán-López, R., Tolosa, O. U. (2017). Relative leaping abilities of native versus invasive cyprinids as criteria for selective barrier design. *Biological Invasions* **19**: 1243-1253.
- Museth, J., Borgstrøm, R., Brittain, J. E. (2010). Diet overlap between introduced European minnow (*Phoxinus phoxinus*) and young brown trout (*Salmo trutta*) in the lake Øvre Heimdalsvatn: a result of abundant resources or forced niche overlap? *Hydrobiologia* **642**: 93-100.
- Museth, J., Hesthagen, T., Sandlund, O. T., Thorstad, E. B., Ugedal, O. (2007). The history of the minnow *Phoxinus phoxinus* (L.) in Norway: from harmless species to pest. *Journal of Fish Biology* **71**: 184-195.
- Neeson, T. M., Ferris, M. C., Diebel, M. W., Doran, P. J., O'Hanley, J. R., McIntyre, P. B. (2015). Enhancing ecosystem restoration efficiency through spatial and temporal coordination. *Proceedings of the National Academy of Sciences* **112**: 6236-6241.
- Nentwig, W., Bacher, S., Kumschick, S., Pyšek, P., Vilà, M. (2018). More than "100 worst" alien species in Europe. *Biological Invasions* **20**: 1611-1621.
- Nentwig, W., Bacher, S., Pyšek, P., Vilà, M., Kumschick, S. (2016). The generic impact scoring system (GISS): a standardized tool to quantify the impacts of alien species. *Environmental Monitoring and Assessment* **188**: 1-13.
- Newman, J. R., Dawson, F. H. (1999). Ecology, distribution and chemical control of *Hydrocotyle ranunculoides* in the UK. *Hydrobiologia* **415**: 295-298.
- Nielsen, C., H.P. Ravn, W. Nentwig, M. Wade (eds.) 2005. The Giant Hogweed Best Practice Manual. Guidelines for the management and control of an invasive weed in Europe. Forest and Landscape Denmark, Hoersholm, 44 pp.
- Noatch, M. R., Suski, C. D. (2012). Non-physical barriers to deter fish movements. *Environmental Reviews* **20**: 71-82.

- Norin, T., Malte, H., Clark, T. D. (2014). Aerobic scope does not predict the performance of a tropical eurythermal fish at elevated temperatures. *Journal of Experimental Biology* **217**: 244-251.
- Northcutt, R. G., Catania, K. C., Criley, B. B. (1994). Development of lateral line organs in the axolotl. *Journal of Comparative Neurology* **340**: 480-514.
- Null, S. E., Viers, J. H., Deas, M. L., Tanaka, S. K., Mount, J. F. (2013). Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat. *Climatic Change* **116**: 149-170.
- O'Farrell, M., Burger, C., Crump, R., Smith, K. (2014). Blocking or guiding upstream-migrating fish: a commentary on the success of the graduated field electric fish barrier. *WIT Transactions on State-of-the-Art in Science and Engineering* **71**: 1-11.
- Parker, A. D., Glover, D. C., Finney, S. T., Rogers, P. B., Stewart, J. G., Simmonds Jr, R. L. (2015). Fish distribution, abundance, and behavioral interactions within a large electric dispersal barrier designed to prevent Asian carp movement. *Canadian Journal of Fisheries and Aquatic Sciences* **73**: 1060-1071.
- Pelicice, F. M., Pompeu, P. S., Agostinho, A. A. (2015). Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. *Fish and Fisheries* **16**: 697-715.
- Pereira, J. L., Vidal, T., Mendes, C., Ré, A., Santos, J. I., Gonçalves, F., Castro, B. B. (2017). Invasive Asian clam distribution pattern reveals minimal constraints to downstream dispersal and imperceptible ecological impacts. *Aquatic Conservation: Marine and Freshwater Ecosystems* **27**: 953-964.
- Pereira, L. S., Neves, R. D. A. F., Miyahira, I. C., Kozłowsky-Suzuki, B., Branco, C. W. C., de Paula, J. C., dos Santos, L. N. (2018). Non-native species in reservoirs: how are we doing in Brazil? *Hydrobiologia* **817**: 71-84.
- Peterson, D. P., Rieman, B. E., Dunham, J. B., Fausch, K. D., Young, M. K. (2008). Analysis of trade-offs between threats of invasion by nonnative brook trout (*Salvelinus fontinalis*) and intentional isolation for native westslope cutthroat trout (*Oncorhynchus clarkii lewisi*). *Canadian Journal of Fisheries and Aquatic Sciences* **65**: 557-573.
- Pounds, J. A., Bustamante, M. R., Coloma, L. A., Consuegra, J. A., Fogden, M. P., Foster, P. N., Ron, S. R. (2006). Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* **439**: 161.
- Pratt, T. C., O'Connor, L. M., Hallett, A. G., McLaughlin, R. L., Katopodis, C., Hayes, D. B., Bergstedt, R. A. (2009). Balancing aquatic habitat fragmentation and control of invasive species: enhancing selective fish passage at sea lamprey control barriers. *Transactions of the American Fisheries Society* **138**: 652-665.
- Rahel, F. J. (2013). Intentional fragmentation as a management strategy in aquatic systems. *BioScience* **63**: 362-372.
- Rahel, F. J., 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.
- Rahel, F. J., McLaughlin, R. L. (2018). Selective fragmentation and the management of fish movement across anthropogenic barriers. *Ecological Applications* **28**: 2066-2081.
- Ricciardi, A., Atkinson, S. K. (2004). Distinctiveness magnifies the impact of biological invaders in aquatic ecosystems. *Ecology Letters* **7**: 781-784.
- Richards, D. C., O'Connell, P., Shinn, D. C. (2004). Simple control method to limit the spread of the New Zealand mudsnail *Potamopyrgus antipodarum*. *North American Journal of Fisheries Management* **24**: 114-117.
- Richardson, R. J., Roten, R. L., West, A. M., True, S. L., Gardner, A. P. (2008). Response of selected aquatic invasive weeds to flumioxazin and carfentrazone-ethyl. *Journal of Aquatic Plant Management* **46**: 154-158.
- Roberts, J. J., Fausch, K. D., Hooten, M. B., Peterson, D. P. (2017). Nonnative trout invasions combined with climate change threaten persistence of isolated cutthroat trout populations in the southern Rocky Mountains. *North American Journal of Fisheries Management* **37**: 314-325.
- Rösch, R., Baer, J., Brinker, A. (2018). Impact of the invasive three-spined stickleback (*Gasterosteus aculeatus*) on relative abundance and growth of native pelagic whitefish (*Coregonus wartmanni*) in Upper Lake Constance. *Hydrobiologia* **824**: 243-254.

- Rosewarne, P. J., Piper, A. T., Wright, R. M., Dunn, A. M. (2013). Do lowhead riverine structures hinder the spread of invasive crayfish? Case study of signal crayfish (*Pacifastacus leniusculus*) movements at a flow gauging weir. *Management of Biological Invasions* **4**: 273-282.
- Ruokonen, T. J., Sjövik, R., Erkamo, E., Tulonen, J., Ercoli, F., Kokko, H., and Jussila, J. (2018). Introduced alien signal crayfish (*Pacifastacus leniusculus*) in Finland - uncontrollable expansion despite numerous crayfisheries strategies. *Knowledge and Management of Aquatic Ecosystems* **419**: 27-36.
- Sartain, B. T., Wersal, R. M., Madsen, J. D., Cheshier, J. C. (2015). Evaluation of six herbicides for the control of water primrose (*Ludwigia peploides* (Kunth) PH Raven spp. glabrescens). *Journal of Aquatic Plant Management* **53**: 134-137.
- Saunders, L. E., Pezeshki, R. (2014). Sublethal effects of environmentally relevant run-off concentrations of glyphosate in the root zone of *Ludwigia peploides* (creeping water primrose) and *Polygonum hydropiperoides* (smartweed). *Weed Biology and Management* **14**: 242-250.
- Schmidt, J. C., Wilcock, P. R. (2008). Metrics for assessing the downstream effects of dams. *Water Resources Research* **44**: 1-19.
- Schneider, E. V., Hasler, C. T., Suski, C. D. (2018). Fish behavior in elevated CO₂: implications for a movement barrier in flowing water. *Biological Invasions* **20**: 1899-1911.
- Schrader, G., Unger, J. G., Starfinger, U. (2010). Invasive alien plants in plant health: a review of the past ten years. *EPPO Bulletin* **40**: 239-247.
- Selck, H., Aufderheide, J., Pounds, N., Staples, C., Caspers, N., Forbes, V. (2006). Effects of food type, feeding frequency, and temperature on juvenile survival and growth of *Marisa cornuarietis* (Mollusca: Gastropoda). *Invertebrate Biology* **125**: 106-116.
- Sharma, S., Jackson, D. A., Minns, C. K., Shuter, B. J. (2007). Will northern fish populations be in hot water because of climate change? *Global Change Biology* **13**: 2052-2064.
- Sherburne, S., Reinhardt, U. G. (2016). First test of a species-selective adult sea lamprey migration barrier. *Journal of Great Lakes Research* **42**: 893-898.
- Shibata, J. Y., Karube, Z. I., Oishi, M., Yamaguchi, M., Goda, Y., Okuda, N. (2011). Physical structure of habitat network differently affects migration patterns of native and invasive fishes in Lake Biwa and its tributary lagoons: stable isotope approach. *Population Ecology* **53**: 143-153.
- Silva, A. T., Lucas, M. C., Castro-Santos, T., Katopodis, C., Baumgartner, L. J., Thiem, J. D., Burnett, N. J. (2018). The future of fish passage science, engineering, and practice. *Fish and Fisheries* **19**: 340-362.
- Simberloff, D., Vitule, J. R. (2014). A call for an end to calls for the end of invasion biology. *Oikos* **123**: 408-413.
- Snow, N. P., Witmer, G. (2010). American bullfrogs as invasive species: a review of the introduction, subsequent problems, management options, and future directions. In *Proceedings of the Vertebrate Pest Conference* (Vol. 24, No. 24).
- Sondermann, M., Gies, M., Hering, D., Schröder, M., Feld, C. K. (2015). Modelling the effect of in-stream and terrestrial barriers on the dispersal of aquatic insect species: a case study from a Central European mountain catchment. *Fundamental and Applied Limnology/Archiv für Hydrobiologie* **186**: 99-115.
- Sorensen, P. W. (2015). Applications of pheromones in invasive fish control and fishery conservation. In *Fish Pheromones and Related Cues* (Sorensen, Wisenden, eds.). John Wiley and Sons, Inc., Ames, USA. pp 255-268.
- Sorensen, P. W., Stacey, N. E. (2004). Brief review of fish pheromones and discussion of their possible uses in the control of non-indigenous teleost fishes. *New Zealand Journal of Marine and Freshwater Research* **38**: 399-417.
- Sousa, R., Novais, A., Costa, R., Strayer, D. L. (2014). Invasive bivalves in fresh waters: impacts from individuals to ecosystems and possible control strategies. *Hydrobiologia* **735**: 233-251.
- Stanley, E. H., Doyle, M. W. (2003). Trading off: the ecological effects of dam removal. *Frontiers in Ecology and the Environment* **1**: 15-22.
- Starrs, T., Starrs, D., Lintermans, M., Fulton, C. J. (2017). Assessing upstream invasion risk in alien freshwater fishes based on intrinsic variations in swimming speed performance. *Ecology of Freshwater Fish* **26**: 75-86.

- Strayer, D. L., Dudgeon, D. (2010). Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society* **29**: 344-358.
- Stuart, I. G., Williams, A., McKenzie, J., Holt, T. (2006). Managing a migratory pest species: a selective trap for common carp. *North American Journal of Fisheries Management* **26**: 888-893.
- Sun, X., He, J., Huang, X., Ping, J., Ge, J. (2008). Growth characters and chlorophyll fluorescence of goldenrod (*Solidago canadensis*) in different light intensities. *Acta Botanica Boreali-Occidentalia Sinica* **28**: 752-758.
- Thwaites, L. A., Smith, B. B., Decelis, M., Fleer, D., Conallin, A. (2010). A novel push trap element to manage carp (*Cyprinus carpio* L.): a laboratory trial. *Marine and Freshwater Research* **61**: 42-48.
- Tickner, D. P., Angold, P. G., Gurnell, A. M., Mountford, J. O., Sparks, T. (2001). Hydrology as an influence on invasion: Experimental investigations into competition between the alien *Impatiens glandulifera* and the native *Urtica dioica* in the UK. In *Plant Invasions: Species Ecology and Ecosystem Management* (Brundu, J., Brock, I., Camarda, L. (eds.)). Leiden, Netherlands: Blackhuys Publishers. 159-168 pp.
- Tierney, K. B., Kasurak, A. V., Zielinski, B. S., Higgs, D. M. (2011). Swimming performance and invasion potential of the round goby. *Environmental Biology of Fishes* **92**: 491-502.
- Tonkin, J. D., Stoll, S., Sundermann, A., Haase, P. (2014). Dispersal distance and the pool of taxa, but not barriers, determine the colonisation of restored river reaches by benthic invertebrates. *Freshwater Biology* **59**: 1843-1855.
- Treanor, H. B., Ray, A. M., Layhee, M., Watten, B. J., Gross, J. A., Gresswell, R. E., Webb, M. A. (2017). Using carbon dioxide in fisheries and aquatic invasive species management. *Fisheries* **42**: 621-628.
- Tsuboi, J. I., Iwata, T., Morita, K., Endou, S., Oohama, H., Kaji, K. (2013). Strategies for the conservation and management of isolated salmonid populations: lessons from Japanese streams. *Freshwater Biology* **58**: 908-917.
- Tucker, M. A., Böhning-Gaese, K., Fagan, W. F., Fryxell, J. M., Van Moorter, B., Alberts, S. C., Bartlam-Brooks, H. (2018). Moving in the Anthropocene: Global reductions in terrestrial mammalian movements. *Science* **359**: 466-469.
- Tudorache, C., Viaene, P., Blust, R., Vereecken, H., De Boeck, G. (2008). A comparison of swimming capacity and energy use in seven European freshwater fish species. *Ecology of Freshwater Fish* **17**: 284-291.
- Van der Walt, J. A., Weyl, O. L., Woodford, D. J., Radloff, F. G. (2016). Spatial extent and consequences of black bass (*Micropterus* spp.) invasion in a Cape Floristic Region river basin. *Aquatic Conservation: Marine and Freshwater Ecosystems* **26**: 736-748.
- Van der Zanden, M. J., Olden, J. D. (2008). A management framework for preventing the secondary spread of aquatic invasive species. *Canadian Journal of Fisheries and Aquatic Sciences* **65**: 1512-1522.
- Verástegui, A. S., Mejía, J. A., Goyburo, A. (2017). Design of a biological corridor for migration of freshwater prawn over a dam in the southwestern slopes of Los Andes, Peru. *Journal of Water Resource and Hydraulic Engineering* **6**: 1-8.
- Verhoef, G. D., Austin, C. M., Jones, P. L., Stagnitti, F. (1998). Effect of temperature on molt increment and intermolt period of a juvenile Australian fresh-water crayfish, *Cherax destructor*. *Journal of Crustacean Biology* **18**: 673-679.
- Verrill, D. D., Berry J. R. (1995). Effectiveness of an electrical barrier and lake drawdown for reducing common carp and bigmouth buffalo abundances. *North American Journal of Fisheries Management* **15**: 137-141.
- Vetter, B. J., Cupp, A. R., Fredricks, K. T., Gaikowski, M. P., Mensinger, A. F. (2015). Acoustical deterrence of silver carp (*Hypophthalmichthys molitrix*). *Biological Invasions* **17**: 3383-3392.
- Videler, J.J. 1993. *Fish swimming*. St. Edmundsbury Press, Bury St. Edmunds, Suffolk, UK. 260 pp.
- Vilizzi, L., Tarkan, A. S., Copp, G. H. (2015). Experimental evidence from causal criteria analysis for the effects of common carp *Cyprinus carpio* on freshwater ecosystems: a global perspective. *Reviews in Fisheries Science & Aquaculture* **23**: 253-290.
- Vitule, J. R. S., Skóra, F., Abilhoa, V. (2012). Homogenization of freshwater fish faunas after the elimination of a natural barrier by a dam in Neotropics. *Diversity and Distributions* **18**: 111-120.

- Vowles, A. S., Don, A. M., Karageorgopoulos, P., Kemp, P. S. (2017). Passage of European eel and river lamprey at a model weir provisioned with studded tiles. *Journal of Ecohydraulics* **2**: 88-98.
- Vukov, D., Jurca, T., Ručando, M., Igić, R., Miljanović, B. (2013). *Cabomba caroliniana* A. Gray 1837 - a new, alien and potentially invasive species in Serbia. *Archives of Biological Sciences* **65**: 1515-1520.
- Wada, T. (2004). Strategies for controlling the apple snail *Pomacea canaliculata* (Lamarck)(Gastropoda: Ampullariidae) in Japanese direct-sown paddy fields. *Japan Agricultural Research Quarterly* **38**: 75-80.
- Wagner, C. M., Jones, M. L., Twohey, M. B., Sorensen, P. W. (2006). A field test verifies that pheromones can be useful for sea lamprey (*Petromyzon marinus*) control in the Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences* **63**: 475-479.
- Wagner, C., Hanson, J., Meckley, T., Johnson, N., Bals, J. (2018). A simple, cost-effective emitter for controlled release of fish pheromones: Development, testing, and application to management of the invasive sea lamprey. *PLoS One* **13**: e0197569.
- Watson, J. M., Coghlan Jr, S. M., Zydlewski, J., Hayes, D. B., Kiraly, I. A. (2018). Dam removal and fish passage improvement influence fish assemblages in the Penobscot River, Maine. *Transactions of the American Fisheries Society* **147**: 525-540.
- Wheatly, M. G. (1989). Physiological responses of the crayfish *Pacifastacus leniusculus* to environmental hyperoxia: I. Extracellular acid-base and electrolyte status and transbranchial exchange. *Journal of Experimental Biology* **143**: 33-51.
- Willis, K., Ling, N. (2000). Sensitivities of mosquitofish and black mudfish to a piscicide: could rotenone be used to control mosquitofish in New Zealand wetlands? *New Zealand Journal of Zoology* **27**: 85-91.
- Willis, S. G., Hulme, P. E. (2002). Does temperature limit the invasion of *Impatiens glandulifera* and *Heracleum mantegazzianum* in the UK? *Functional Ecology* **16**: 530-539.
- Wittmann, M. E., Chandra, S., Reuter, J. E., Schladow, S. G., Allen, B. C., Webb, K. J. (2012). The control of an invasive bivalve, *Corbicula fluminea*, using gas impermeable benthic barriers in a large natural lake. *Environmental Management* **49**: 1163-1173.
- Wittmann, M. E., Cooke, R. M., Rothlisberger, J. D., Lodge, D. M. (2014). Using structured expert judgment to assess invasive species prevention: Asian carp and the Mississippi Great Lakes hydrologic connection. *Environmental Science and Technology* **48**: 2150-2156.
- Xiong, W., Wang, H., Wang, Q., Tang, J., Bowler, P. A., Xie, D., Wang, Z. (2018). Non-native species in the Three Gorges Dam Reservoir: status and risks. *BioInvasions Records* **7**: 153-158.
- Yoshida, K., Matsukura, K., Cazzaniga, N. J., Wada, T. (2014). Tolerance to low temperature and desiccation in two invasive apple snails, *Pomacea canaliculata* and *P. maculata* (Caenogastropoda: Ampullariidae), collected in their original distribution area (northern and central Argentina). *Journal of Molluscan Studies* **80**: 62-66.
- Yu, S., Wages, M. R., Cai, Q., Maul, J. D., Cobb, G. P. (2013). Lethal and sublethal effects of three insecticides on two developmental stages of *Xenopus laevis* and comparison with other amphibians. *Environmental Toxicology and Chemistry* **32**: 2056-2064.
- Zaiko, A., Olenin, S., Daunys, D., Nalepa, T. (2007). Vulnerability of benthic habitats to the AIS. *Biological Invasions* **9**: 703-714.
- Zhang, Z. Y., Zheng, X. M., Ge, S. (2007). Population genetic structure of *Vitex negundo* (Verbenaceae) in Three-Gorge Area of the Yangtze River: the riverine barrier to seed dispersal in plants. *Biochemical Systematics and Ecology* **35**: 506-516.
- Zhu, Q., Moser, M., Kemp, P. (2011). Numerical analysis of a unique mode of locomotion: vertical climbing by Pacific lamprey. *Bioinspiration and Biomimetics* **6**: 016005.
- Zielinski, D. P., Voller, V. R., Svendsen, J. C., Hondzo, M., Mensinger, A. F., Sorensen, P. (2014). Laboratory experiments demonstrate that bubble curtains can effectively inhibit movement of common carp. *Ecological Engineering* **67**: 95-103.