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Applications of biosensors to overcome monitoring challenges in freshwater invasive species

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Abstract

Global technological advances have boosted the discovery of new tools that have increased the ability to obtain large and high-quality ecological data with the potential to rapidly develop knowledge on how species behave and interact in ecosystems. Comprehensive time-series datasets on the in situ behaviour and dispersal of wild organisms are essential for addressing fundamental ecological and physiological questions regarding invasive freshwater species. In this review, we address how biosensors can be useful in assessing movement, internal states, behaviour, and data of the surrounding environment in freshwater invasive species considering the state of the art and also discussing possibilities of research for the near future.

For this, we performed a systematic review of the available literature and retrieved a total number of 132 scientific studies corresponding to 140 records of sensors being used. Most studies used radio telemetry (40%; n=53) followed by acoustic telemetry (34%; n=45) and PIT telemetry (20%; n=26) to study invasive species. The taxonomic group most studied was fish (72%; n=109), followed by crustaceans (14%; n=21) and amphibians (5%; n=8). The most addressed topics included species behaviour assessment (72%; n=101), species physiology (10%; n=14) and management (9%; n=12). The number of studies started noticeably increasing since 2006, with the majority of them being performed in North America (55%; n=73), followed by Europe (30%; n=40) and Oceania (7%; n=9). The collected information provided by biosensors can be useful to better understand the dynamics and impacts of cryptic invasive species and can be applied in the management of biological invasions.

We also address future directions concerning the use of biosensors in freshwater invasive species (e.g. underwater internet systems, artificial intelligence, crittercams). Overall, these technologies provide unique possibilities in the field of biological invasions in freshwater ecosystems and the development of new technologies to address their limitations will increase the amount and reliability of the data gathered with possible payoffs on the management process.

Keywords: Biosensor; Conservation; Freshwater; Invasive species; Management;

Introduction

The introduction of invasive alien species (IAS) has dramatically altered terrestrial and aquatic ecosystems and is now an important driver of biodiversity change, costing enormous resources to manage their impacts (Pyšek et al. 2020; Diagne et al. 2021). Although no ecosystem is immune to the invasion of novel species, freshwater ecosystems can be particularly affected by high ecological and economic impacts (Strayer 2010; Cuthbert et al. 2021). Ecological impacts of IAS include the disruption of food webs, changes in nutrient cycling, and modifications in physical characteristics due to ecosystem engineering, with cascading effects on biodiversity at all trophic levels (Sousa et al. 2009; Gallardo et al. 2016; Gutiérrez et al. 2014). Concurrently, IAS can generate severe economic impacts, including biofouling of structures, changes in fisheries yields, and management costs, among others (Cuthbert et al. 2021).

The growing number of species introduced to freshwater ecosystems and their subsequent establishment highlights the urgent need for more effective measures to monitor and manage IAS (Strayer, 2010). However, studying IAS in the natural environment can be challenging, particularly for species that are cryptic, shy, or avoid humans or for species that colonize habitats where direct observations can be difficult (Rutz and Hays 2009). The study of IAS in freshwater ecosystems exemplifies some of these difficulties, where high turbidity, fast river flow, and deep rivers and lakes, among others, may make the logistics and financial investment for in-situ monitoring highly demanding and unrealistic. Despite possible difficulties, the reality is that we need a better assessment of the basic ecological and physiological features of IAS to provide insights into fundamental ecological and evolutionary questions and to contribute to more efficient and effective management measures, from prevention to control, based on sound scientific data (Gurevitch et al. 2011; Ricciardi et al. 2021).

Technology has helped to overcome some of the field monitoring challenges described above by remotely measuring key ecological features of species. Technological advances in the last decade have improved the development of new tools, enabling us to gather larger amounts and high-quality data that can accelerate our knowledge of how individuals, populations, and communities behave and interact in ecosystems (Besson et al. 2022; Costa-Pereira et al. 2022; Couzin and Heins 2022; Jetz et al. 2022). A clear example of this was the combined use of GPS tracking data and aerial imagery to assess what habitat and social features influence the movement of wild baboons (*Papio anubis*) in Kenya (Strandburg-Peshkin et al 2017). In the marine realm, Goldbogen et al. (2017) applied a multi-sensor camera tag on whales to study their biomechanics. This technology allowed the determination of whale's inhalation and exhalation timing, how their feeding synchronizes with depth and speed, and the timing of mouth opening, maximum gape, and mouth closure among other behaviours. These tools can also be useful to improve our understanding of the physiology, behaviour, and ecology of IAS and allow a more accurate assessment of ecological and economic impacts (Lennox et al. 2016, 2017, 2023; Katzner and Arletazz 2020; Alós et al. 2022). In addition, some of these technologies can enhance spatial, temporal, and taxonomic coverage of monitoring and have the potential to increase our understanding of the role of IAS on ecosystem functioning and dynamics. If multiple technologies can be integrated, and contribute to open data, it can open the door for new questions about IAS at different ecological levels that were mostly impossible to ask until recent times.

New technological solutions are now increasingly available to better understand IAS ecology and particularly useful may be the use of biosensors (Lahoz-Monfort and Magrath 2021). By definition, the field of electronic tagging and tracking applies to studies where animals are remotely sensed using electronic tools (Fahlman et al. 2021). Data can either be logged or transmitted by satellite, Global System for Mobile (GSM) communications, or other means such as radio frequency or acoustic transmissions. Dataloggers placed on organisms are referred to as biologgers, but loggers can also be placed in or above water to measure climatic variables, record sounds or images, or take other remote measurements (Lahoz-Monfort and Magrath 2021). Transmitters must be in the air to send data via satellite or GSM but can send data to fixed stations by radio or acoustic telemetry where the data are logged for later download; when transmitters are affixed or implanted in animals it is often referred to as animal biotelemetry. Collectively, animal biologging and biotelemetry can be considered as a field of electronic tagging and tracking which is defined in this systematic review as biosensors. For example, Raby et al. (2020) used biosensors to compare the habitat use of the native lake trout (*Salvelinus namaycush*) to the invasive Chinook salmon (*Oncorhynchus tshawytscha*) and found these species to display different foraging tactics and behaviours, which allowed them to co-exist despite having similar diets.

This study reviews the bibliography available concerning the use of biosensors in freshwater IAS to assess: i) spatial-temporal patterns of published studies; ii) the breadth of the type of sensors used; iii) and most studied taxonomic groups. It also discusses and provides preliminary insights on the potential application of these devices in advancing our understanding of freshwater biological invasions in the future.

Literature search and review

A scientific literature search was conducted using Web of Knowledge (www.webofscience.com), for published research associating non-invasive sensors and invasive species. The search was based on an exhaustive compilation of search terms (See Supplementary material), including common terms (e.g. "biosensing", "invasive species", "non-native*"), and specific terms for non-invasive sensors (e.g. "telemetry", "acoustic", "PIT*tag*"). All peer-reviewed studies discussing the use or using non-invasive sensors published up to December 31, 2023, were considered. However, only records reporting non-invasive sensors directly attached to the species' body, studies involving invasive species, and studies developed on freshwater (or adjacent riparian) ecosystems were retained, while records from reviews or meta-analyses that did not add any new relevant information were excluded to avoid double counts. The publications were reviewed and discussed by the authors to ensure they were relevant to our objectives. In addition, other studies corresponding to our search, known by the authors, but that did not appear in the search results were added to the list.

Each study was classified by sensor type used (e.g. acoustic telemetry, heart sensor, infrared sensor), output (i.e. what the sensor measured), and function (i.e. what it had been used for). In addition, data on the geographic location (i.e. country and continent), the taxonomic group of the invasive species studied (i.e. amphibian, crustacean, fish, mammal, molluscs, plant, reptile), and year of publication were also collected.

The number of papers published per year on the subject was plotted between 1996 (the year of the first record) and 2023, and a Sankey diagram was generated to illustrate the linkage among records on different sensor types, output, and functions, based on the taxonomic group, using the R-package "networkD3" (Allaire et al. 2017). In addition, a heatmap of the total number of scientific publications on the subject per continent was also produced.

General description of the dataset

After excluding records that did not match our criteria (i.e. studies on freshwater or riparian IAS using non-invasive attached sensors), the final dataset comprised 132 scientific publications, which corresponded to 140 case studies as six publications used more than one sensor, mostly conducted in rivers (50%; n=66), lakes (~27%; n=35), and controlled environment (e.g., laboratory and mesocosms) (~8%; n=11). A total of 15 different sensor types were identified and comprised acceleration data loggers, acoustic telemetry, hall sensors, heart sensors, Heat Pulse Velocity (HPV) systems, inductive proximity sensors, infrared sensors, PIT telemetry, pop-off tags, pressure sensing panels, pressure sensitive tags, radio telemetry, thermal dissipation sensor, time-depth recorder, and ultrasonic telemetry (Figure 2). Telemetry-based sensors that transmit data rather than log it on-board were the most well represented, accounting for 125 (~95%) studies (Figure 1). These sensors were used to study species behavior, management, monitoring, biological interactions, co-occurrence, physiology, and survival, but also to develop methodologies to be used in future studies (Figure 2). The majority of the 140 case studies (~72%; n=101) focused on species behavior, of which 18 reported a second function for the sensor (species management, n=6; physiology, n=5, and monitoring, n=4 each, and methodology, n=2; and interactions with other species, n=1). Invasive fishes were the most studied taxonomic group with 108 (~82%) studies, followed by crustaceans (n=21; ~16%), amphibians (n=8; 6%), mammals (n=6; ~5%), and molluscs and plants, each presenting 3 studies (~2%), and reptile (n=2; ~2%) (Supplementary material). One paper (i.e., Cavallo et al. 2013) studied the effects of an invasive predator by applying the sensor to the native fish species instead of the invader. The most studied invasive species was *Cyprinus carpio* (n=21; ~14%), followed by *Petromyzon marinus* (n=11; ~7%), *Hypophthalmichthys molitrix* (n=9; ~6%), and *Pacifastacus leniusculus* and *Ctenopharyngodon idella* and (n=8; 5%, each).

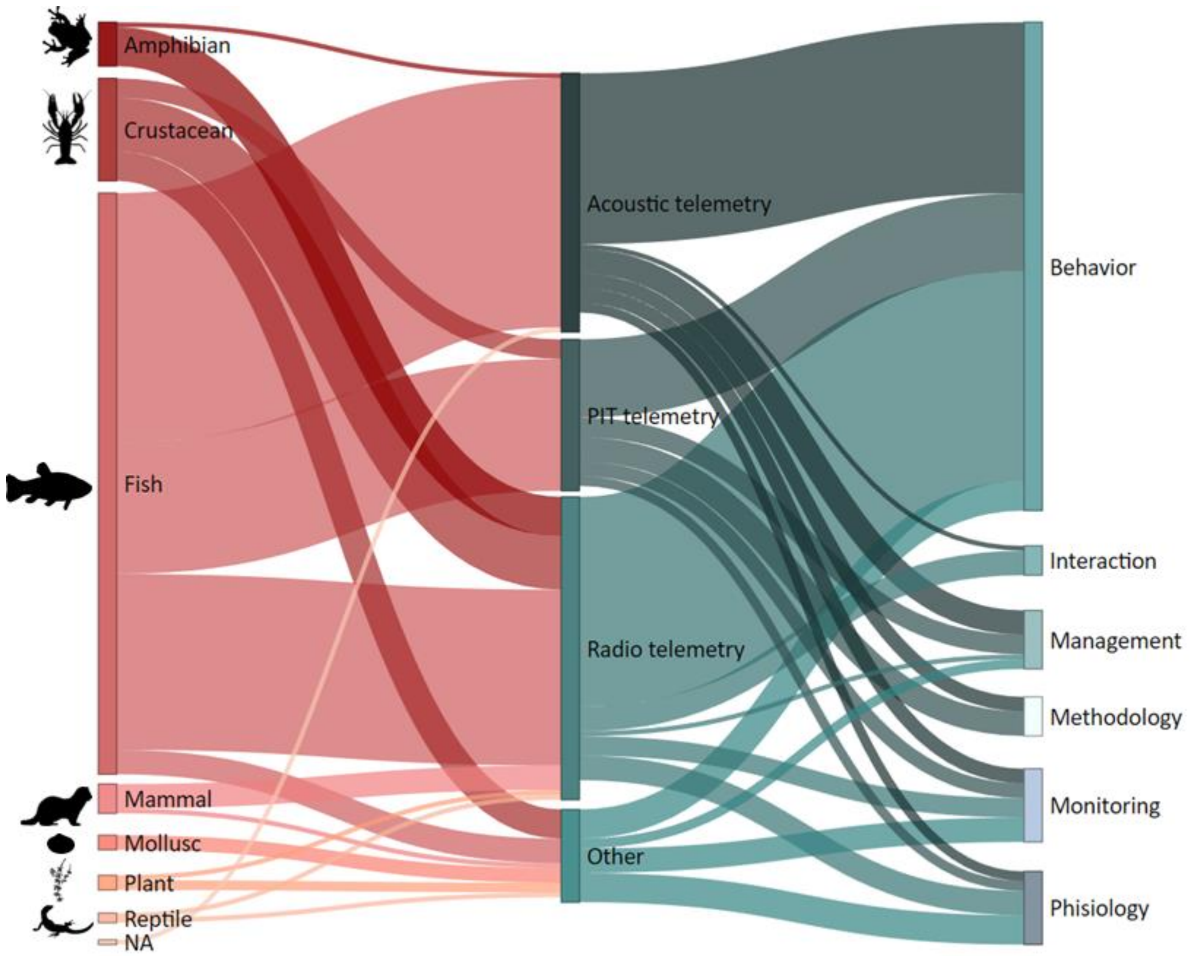

Figure 1. Linkage among the relative quantity of published records on biosensors in invasive species by major taxonomic group, type of biosensors used, and functions assessed. The "Other" category includes hall sensor, heart sensor, HPV system, inductive proximity sensor, infrared sensor, micro acceleration data loggers, pop-off tags, pressure sensing panels, pressure sensitive tags, thermal dissipation sensor, time-depth recorder, and ultrasonic telemetry.

The records were collected from 22 countries. Most studies (55%, n=73) were conducted in North America, the USA being the country that contributed the most with 62 studies. Of the retrieved studies, 40 (30%) were conducted in Europe, followed by Oceania with 9 (~7%) (all conducted in Australia), Asia with 5 (~4%), Africa (South Africa) with 3 (~2%), and lastly South America with 2 (~2%). Aside from the USA, the countries that contributed the most with research using sensors were the Canada and United Kingdom (n=11; 8%, each), Australia (n=9; ~7%, each), and the Czech Republic (n=8; 6%). The other countries published 4 (~3%) or less studies.

Studies performed in North America focused mostly on invasive fishes (n=73; ~76%; eight of the case studies used more than one species), which follow similar trends as reported in the general results (Figure 2). Mammals were the only taxonomic group that was not studied. European studies included less taxonomic groups but were less biased, being fishes and crustaceans the most studied groups (n=26, 51%; and n=19, 37%, respectively). Mammals (n=4; ~8%), amphibians and molluscs (n=1; ~2%, each) were less studied. Research from other continents was limited to a few taxonomic groups (Africa: fishes and plants, n=2 and n=1, respectively; Asia: fishes and reptiles, n=4 and n=1, respectively; and Oceania: amphibians and fishes, n=6 and n=3, respectively) or only one group (South America: mammals, n=2).

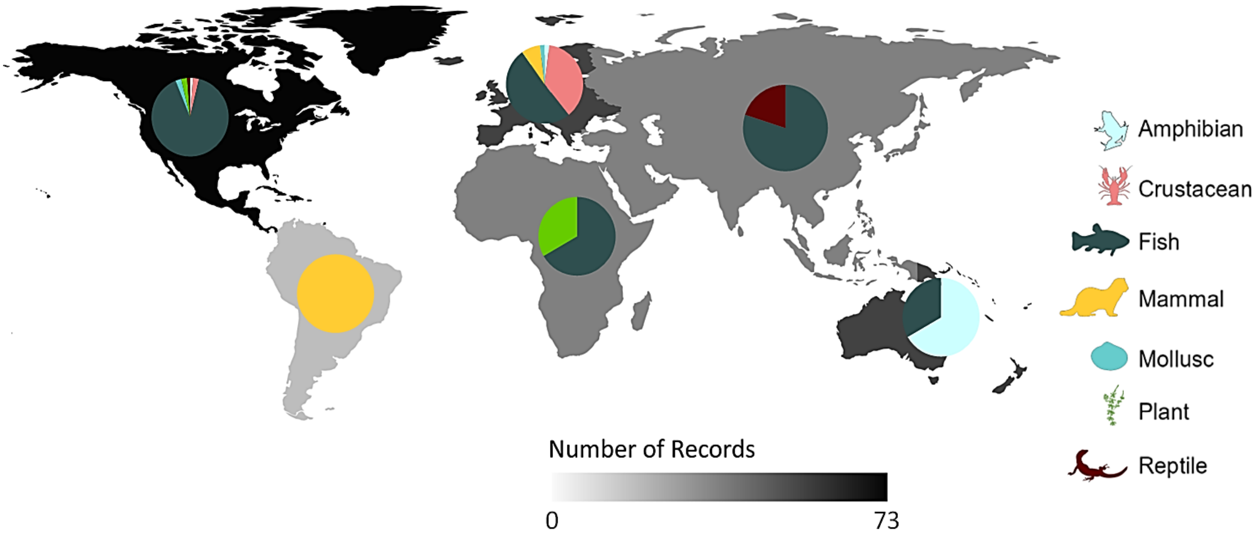

Figure 2. Geographic patterns of published studies using biosensors in invasive species by taxonomic groups.

The number of studies generally increased through the years, with the earliest published paper found in 1996 (i.e., Allen et al. 1996; Figure 3). The first study published originated from North America (USA), while records from other continents date back from 1998 (Europe; Ireland) (i.e., Donnelly et al. 1998), 2006 (Oceania; Australia) (Brown et al. 2006), 2012 (Asia; Japan) (i.e., Honda et al. 2012) and 2013 (Africa and South America; South Africa, Kadye and Booth 2013; and Chile, Medina-Vogel et al. 2013, respectively). Studies from Europe and North America have been published at a constant pace except for the years 2001, 2006, and 2011, for Europe, and the years 1999–2002, and 2004–2006, for North America. Annual publication in North America averaged 2.7 publications per year, while an average of 1.5 papers from Europe was published per year since the first publication on the subject. However, while the rate of publications for Europe has been constant over the years, North America had an increase in published studies over the years, attaining the maximum of 15 publications, in 2021, against only 2 publications from Europe.

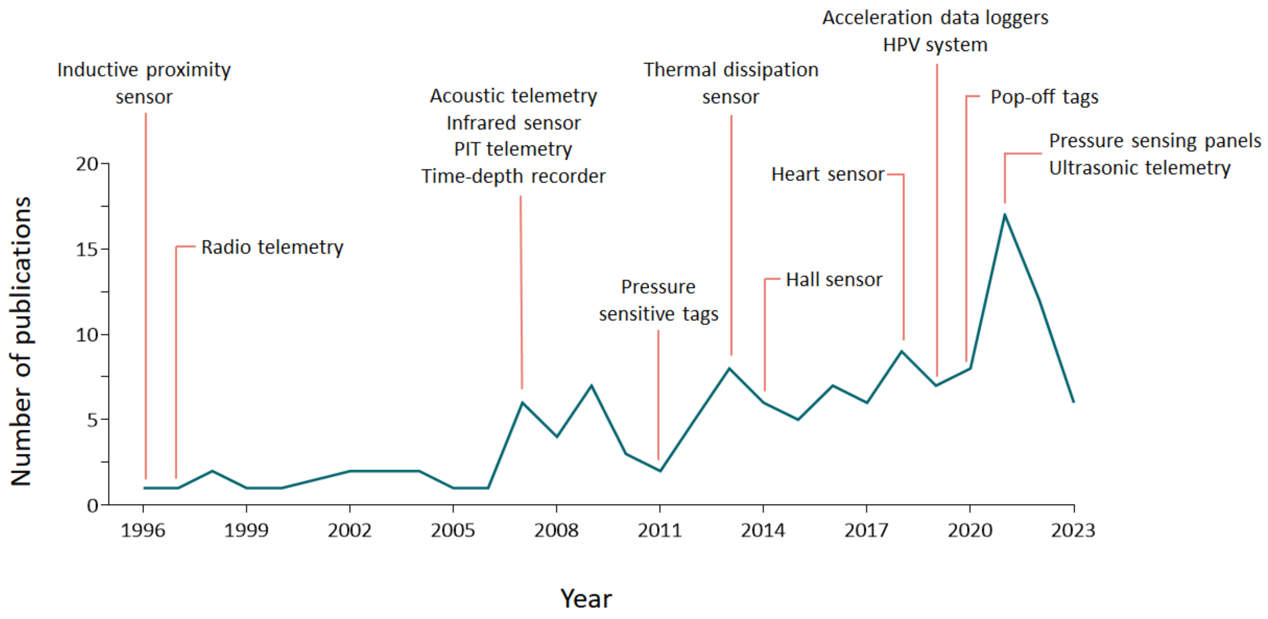

Figure 3: Number of publications per year on the use of biosensors to study invasive species in freshwater systems. Milestones represent the first record of the use of each identified sensor in an invasive freshwater species.

Regarding the type of sensors used, studies from North America encompass more diversity of sensors (n=11). Acoustic, PIT, and radio telemetry were the most frequently applied technologies (n=33, ~42%; n=21, ~27%; n=16, ~21%, respectively). Research in Europe was conducted using 7 different sensors, with radio telemetry the most used technique (n=26; ~62%). In Oceania (Australia), studies used acoustic (n=2; 20%) and/or radio telemetry (n=8; 80%), while research from Africa (South Africa) used either HPV systems (n=1; ~33%) or acoustic telemetry (n=2; ~67%). Studies from Asia used acoustic telemetry (n=3; 60%), or acceleration data loggers or radio telemetry (n=1; ~33%, each). Both studies conducted in South America used radio telemetry.

In terms of application, 20 studies (~15%) used the sensors for two purposes. As referred before, species behavior was the most frequent focus of study (~72%; n=101), whether as a unique application of sensors (n=83) or jointly with another application (n=18). This category includes the assessment of natural behavior, and natural movement or changes in movement in response to the environment. It was followed by species physiology (n=14; 10%), species management (n=12; ~9%), species monitoring (n=11; ~8%), which included dispersal dynamics, the development of methodologies (n=8; ~6%), and species interactions (n=6; ~4%). Research from North America followed the same patterns, being sensors mostly used to study species behavior (n=55; ~71%), followed by species management (n=11; ~14%), monitoring and methodology (n=7; ~9%, each), physiology (n=5; ~6%), and species interaction (n=3; ~4%). In Europe, researchers focused on studying species behavior (n=31; ~74%), followed by species physiology (n=6; ~14%), species interaction (n=3; ~7%), monitoring (n=2; ~5%) while only one paper applied sensors for management (~2%). Studies from Oceania only used sensors for three applications: behavior (n=8; 80%), physiology (n=2; 20%), and monitoring (n=1; 10%). In Asia, sensors were only used to study species behavior (n=4; 80%) and develop methodologies (n=1; 20%), while in Africa sensors were used for species behavior and monitoring (n=2 and n=1; ~67% and ~33% respectively) and in South America for species behavior and physiology (n=1; 50% each).

Applications and their potential for management

Biosensors used to assess movement have the potential to inform population dynamics and support predictions on species dispersal at relevant spatial and temporal scales. Movement of IAS can change with time, environmental conditions, and position (i.e. individuals from the core and front of the invasion), such is the well-known case of the invasive cane toad (*Bufo marinus*) (Phillips et al. 2006). The dispersal of this species in Australia was compared between invasion core and front using radio telemetry, and evidence was found that the current dispersal rate at the front is much higher than at early invasion fronts and current established populations (Alford et al. 2009). This evidence may indicate a behavioural and/or environmental change at the intraspecific (and even intra-population) level, which can lead to a better understanding of the invasion processes and the range of impacts they can have on native species. Frequently, the focus is placed on impacts and biological features at the species level, including in invasion ecology. However, given the importance of environmental filtering and/or biotic resistance, these impacts or features can be highly context-dependent and should be assessed at the population level (Simberloff et al. 2013; Haubrock et al. 2024). It is also important to note the type of system invaded and the connectivity between systems as the dispersal of IAS is dependent on their ability to move to a new area. Such types of studies can only be performed in connected aquatic systems or with semi-aquatic species that can reach disconnected areas. Considering the above-mentioned case of the cane toads in Australia, we may even think of these impacts and biological features changing at the intra-population and individual levels and the use of biosensors can be extremely informative in these assessments. With the application of acoustic tags on the native Chinook salmon, *Oncorhynchus tshawytscha*, it was possible to evaluate the effects of non-native piscivorous fish on this species' survival (Cavallo et al. 2013). By removing the non-native predator, the survival of tagged salmon increased significantly, further highlighting the use of sensors to study the impacts of invasive species.

IAS adapt to the new conditions of the invaded habitats, including establishing new biological interactions with co-occurring native species. Sensors can be used to assess these new interactions and, for example, Stakėnas et al. (2013) used radio telemetry to assess the possible interactions of the invasive pumpkinseed (*Lepomis gibbosus*) and the native brown trout (*Salmo trutta*). Both species occupied the same habitat; however, they presented slightly different environmental preferences with the brown trout opting for microhabitats with higher water velocity, coarser substrate, and sometimes deeper waters compared with pumpkinseed. Although their range overlapped and changed similarly throughout the seasons, the range area of brown trout was larger, with the absence of mutual attraction or avoidance, which indicates minimal, to no impact of the invasive pumpkinseed on the native brown trout. Therefore, at the interspecific level, it is possible to use biosensors to assess avoidance behavior (i.e., moving away from or avoiding the same areas as other species or conspecifics) and changes in the physiology of native species before and after an invasion. For example, the invasive spinycheek crayfish (*Faxonius limosus*) and native juvenile burbot (*Lota lota*) have an overlapping nocturnal foraging phase. By applying PIT-tags on both crayfish and fish, researchers found that *L. lota* showed a strong avoidance response to the presence of crayfish. However, this behavior was age-dependent since it was only observed in age-0 burbot, which indicates that the invasive crayfish mostly predate the young-of-the-year cohorts (Hirsch and Fisher 2008). These results show the potentially considerable negative effects of the invasive species on the native fish population. In another case study, Salo et al. (2008) followed the movement of the invasive semi-aquatic American mink (*Mustela vison*) by radio-tracking and found that predation risk by a native top predator, *Haliaeetus albicilla* (white-tailed sea eagle), reduced mink's swimming distances. These results suggest that this behavioural change may impair mink's nutrition and ultimately reduce mink population growth, mitigating its negative impacts on the invaded ecosystems.

Using hall sensors, freshwater bivalves were found to recognize and respond to the presence of invasive signal crayfish *Pacifastacus leniusculus* by closing their shells and showing an irregular shell movement compared to controls (Alexandra Meira, unpublished data). This was particularly observed after bivalves had had previous contact with the signal crayfish and showed the potential stress mediated by this predator on native bivalves. Such responses indicate possible non-lethal impacts of invasive crayfish on native bivalves (e.g., reduced filtration rates), but also bivalve defence mechanisms and adaptability, which is a piece of valuable information to fully understand and assess the effects of these species in invaded environments. Therefore, by assessing physiological and behavioural responses, biosensors may inform on the impacts of IAS and on potential changes in distribution ranges or activity levels that could ultimately help the conservation of the native species and control of IAS.

Predation of native species can also be recorded using telemetry-based tags. Boulêtreau et al. (2020) used acoustic and radio tags on native sea lampreys (*Petromyzon marinus*) to assess the risk of predation by the invasive European catfish (*Silurus glanis*). Tags were equipped with a biopolymer that, in case of predation, would change the tag ID making it possible to identify tagged lampreys that were eaten. The results showed that 80% of the tagged sea lampreys were preyed upon within a month and 50% were preyed 8 days after tagging, indicating the strong impacts the invasive predator can have on this native species with high ecological and economic value in the studied region.

The use of sensors has also been applied to assess intra and interspecific variation regarding environmental conditions. For example, in the United States, the movement of the invasive silver carp (*Hypophthalmichthys molitrix*) was assessed regarding phenological and environmental factors (Coulter et al. 2016). This study found that silver carp moved upstream in the spring, before the beginning of spawning, and downstream in the fall. The characteristics of the movement (i.e., movement rates, movement distance, and movement direction) also changed between seasons. Despite high individual variability, the results showed patterns related to seasons and locations that could potentially be used for early detection and control. While both native spinycheek crayfish (*Astacus astacus*) and invasive signal crayfish (*Pacifastacus leniusculus*) displayed similar nocturnal behavior, using non-invasive infrared sensors, Styrishave et al. (2007) found that *P. leniusculus* presented higher activity (heart rate and locomotor activity) during daytime than *A. astacus*. Therefore, it could be possible to use these daytime differences to target *P. leniusculus* for control measures. More recently, Bopp et al. (2023) conducted a similar study that used acoustic telemetry to find differences between the timing and duration of migration of the invasive grass carp (*Ctenopharyngodon idella*) and the native walleye (*Sander vitreus*). These behavioural differences can assist the selection of an optimal timing and locations to deploy control barriers and effectively block the movement of grass carps to new habitats without affecting the native walleye. Thus, biosensors can assist the management of invasive species by providing the information needed to apply specific and effective measures.

Given the high ecological and economic impacts mediated by IAS in freshwater ecosystems with no signs of deceleration in the number of introductions for the near future (Seebens et al. 2017), management becomes a key aspect when dealing with these species. Therefore, the application of biosensors to management could be an interesting tool that could help in the design of the best actions to prevent, detect, eradicate, or control invasive species in freshwater ecosystems (Figure 4).

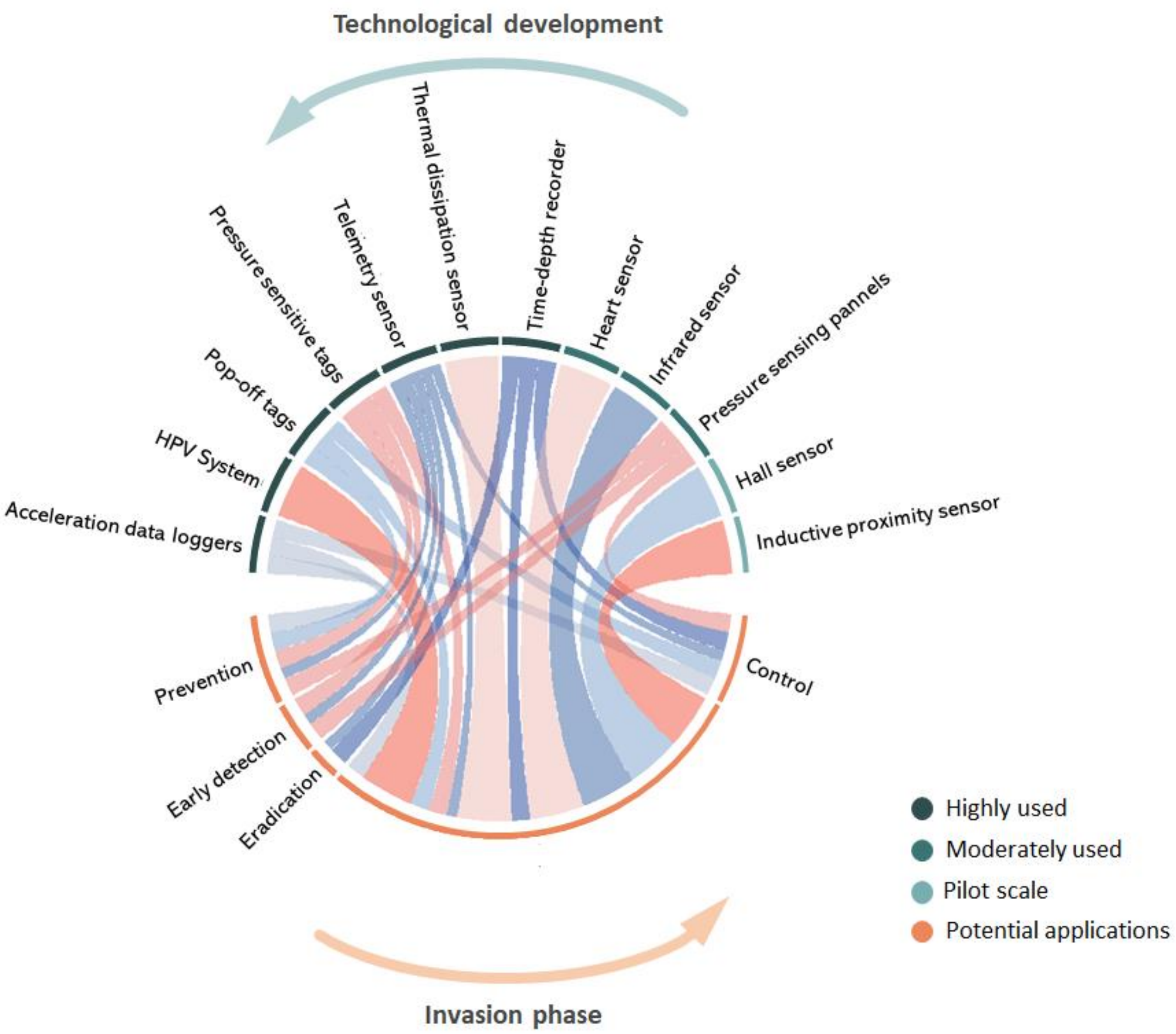

Figure 4. The level of development of biosensors identified throughout the studies gathered and their potential application in the management of invasive species. The level of development was classified based on how much is known about the sensor, its user accessibility, and how recurrent its application is in the study and management of invasive species.

Regarding prevention, the use of biosensors could give insights into the physiological tolerances of the species. This data could help generate more accurate species distribution models (SDMs) (i.e.. the mechanistic vs. correlative SDMs). These more accurate mechanistic models can be used to better predict the areas that will be more susceptible to invasion (Elith et al. 2010; Gallien et al. 2010; Evans et al. 2015), making this information essential to implement prevention and early detection measures at finer spatial scales. In this scope, sensors can allow the identification of invasion expansion patterns, and this can support early detection of first invaders in particular areas. This data could be potentially useful to identify structure locations (e.g., traps and barriers) that might be deployed to effectively eradicate or at least control IAS.

Managing the expansion of IAS and assessing their impacts can be very laborious, expensive, and inefficient, and as IAS spread the logistic and financial costs often increase. The Judas technique can be a reliable and efficient way to control and contain these invasions with cost-effective benefits compared to other ways. Bajer et al. (2011) showed high removal rates (52–94%) of the common carp (*Cyprinus carpio*) from lakes in south-central Minnesota USA by using Judas fish that were radio-tagged coupled with pressure-sensitive tags, to locate winter aggregations of this species and remove them with seine nets. Kennedy et al. (2018) showed that this technique can also be used in small flying invertebrates, such as Asian hornets (*Vespa velutina*), which are common in riparian habitats (Monceau et al. 2012). The early detection and removal of the nests is considered the only option to control the invasion of this IAS. They have used radio telemetry to successfully detect the location of the nests, by attaching a 0.28g tag to hornet workers with a 0.8 tag: hornet weight ratio. They reported a 100% and 63% success rate in tracking the tagged hornets, and previously unknown nests detection, respectively. In this case, this method can also be used for early nest detection.

Future directions

Many improvements and new approaches could be developed to exploit the full potential of biosensors to study IAS. In this section, we share our thoughts about the future directions concerning this topic following a hierarchical order, from research studies and management actions that can be implemented without new technological advances to more challenging and ambitious directions that still need further technological developments.

Although it has not been apparent from the last two years, possibly due to the constrains caused by the covid-19 pandemic, it is possible there will be a significant increase in the number of studies published. The number of studies published on the subject decreased significantly after 2021More studies should use biosensors to investigate how IAS interacts with other global stressors such as climate change, habitat loss and fragmentation, and pollution. For example, how warming may affect the behavior and impacts mediated by IAS, especially those species that are poikilothermic; how the presence of physical obstacles in rivers may affect the dispersal of IAS; and how pollution or land use may influence the physiology and behavior of IAS. Similar studies were conducted with native species (e.g., Moser and Lindley 2007; Hayden et al. 2014; Wilson et al. 2018) and could therefore be easily adapted to IAS. These assessments could contrast native and non-native species and determine if they respond differently to these human disturbances, which could inform on the possible evolutive advantages of IAS compared to native species in more disturbed ecosystems. Such approaches will likely require experimental manipulations to isolate the effects of climate (or other stressors) on the responses measured by electronic tagging, being possible outcomes relevant to better understanding the invasion process. However, mensurative approaches may also yield important outcomes if study designs are appropriately replicated, such as among replicated pond environments.

Nowadays, biosensors have some combination of the following caveats that restrict their applications, such as size/weight influencing smaller species behavior, long-distance communication, signal interference, battery life, data storage, and processing. Although some recent examples already include invertebrates such as bivalves, in practice, this technology is mainly applied to larger animals such as crayfish and fish. However, recent advancements will make this application possible for very small organisms without impairing their normal behavior. A recent study with terrestrial gastropods showed how millimetre-sized smart sensors can be used in native and non-native snails (Bick et al. 2021) and this technology can be applied to small aquatic species.

While some well-known and described examples of the use of biosensors in the control of invasive species exist, such as the “Judas technique” described previously (Bajer et al. 2011), this type of application is only possible for the management of gregarious species or populations with low individual behavioural variability. When using radio telemetry to assess the spatial behaviour of the invasive crayfish *Procambarus clarkii*, Gherardi et al. (2002) could not find clear movement patterns at the population level. Indeed, movement was not related to sex, hour of the day, or other abiotic and biological features measured except water depth and crayfish size, which both appear to increase crayfish speed, making it impossible to develop a methodology as efficient as the “Judas technique” to control and possibly eradicate these populations. Nonetheless, it is essential to determine such behavioural patterns, especially as a last resort when addressing species that are already established and are thus unlikely to be eradicated, demanding new solutions that can only be found through relevant information collected by biosensors.

In terms of communication signalling, the information gathered is nowadays dependent on the presence of deployed structures and is highly impaired by detrimental environmental conditions. For example, radio frequency transmissions underwater can only work effectively at short distances due to being highly affected by propagation loss, which is conditioned by salinity and temperature, among other environmental characteristics (Gussen et al. 2016). This shortcoming can be overcome using optical or acoustic transmissions; however, these are also dependent on environmental conditions such as water turbidity and density. Acoustic transmissions can reach higher distances but can have lower throughput and latency at long distances, which is dependent on water depth, salinity, and temperature (Gussen et al. 2016). Thus, new systems and solutions need to be developed to solve or mitigate these limitations. One possible solution could be the application of underwater internet systems. Shihada et al. (2020) produced a system that requires off-the-shelves components that reduce the cost of production and, it relies mainly on optical communications for medium distances, including LED and laser light signals, and does not require additional infrastructures as it can operate using batteries and low-power devices making its use more flexible and practical. However, limitations such as high water turbulence reduce the quality of the communication channel, causing interference and dispersion of the signal. Several methods similar to this have been proposed in the last few years and while many challenges have been identified, these advancements might offer viable opportunities for underwater communication (e.g., incorporation of smart sensors to overcome and optimize the interpretation of signal noise) and data acquisition for scientific research (Kao et al. 2017; Mohsan et al. 2023).

Apart from the communication of data, there is also the problem of analysis given the amount of data gathered and stored by biosensors. Artificial intelligence (AI) could be used to support the analysis process by modelling or automatically informing on IAS movements and interactions using real-time transmissions with live-buoys or satellites. AI is dependent on machine learning (ML) and has already been applied in ecological studies such as behavioural studies (e.g., Browning et al. 2018; Norouzzadeh et al. 2018; Nath et al. 2019), population monitoring (e.g., Norouzzadeh et al. 2018; Guirado et al. 2019), and identification of species (Knight et al. 2017; Salamon et al. 2017; Tabak et al. 2019). The latter is often associated with community science projects through citizens assisting with the validation of the results or using smartphone applications built with AI to identify the species in their surroundings (McClure et al. 2020). Thus, the incorporation of AI tools in ultra-low power wireless integrated circuits (IC's) with sensor automation systems or imaging of cameras (see below), augments direct applications for automotive data processing and enhances data accessibility in public databases, which could therefore allow faster detection responses to IAS at a broader scale.

The use of animal-mounted cameras (crittercams) for identifying and monitoring IAS represents a promising path for research and conservation efforts. With the integration of AI and ML, the efficiency and accuracy of species identification from crittercam footage could be greatly enhanced, and the development of software capable of real-time identification could facilitate the data analysis process and provide suitable and fast feedback for conservation actions. By combining movement sensors, crittercams, and ML to develop a method to automatically detect and geolocate behaviours for the flatback turtle (*Natator depressus*), Hounslow et al. (2023) showed its potential for management and mitigation of threats by prioritizing the protection of important specific behavior locations (i.e., rest and forage). The same strategy could be applied to protect native species from IAS. Expanding the scope of crittercams to encompass multiple species within a system could allow us to better understand the population dynamics of species and community-level impacts, which could ultimately help select meaningful management actions. Additionally, the long-term grouped application of crittercams, biosensors, and AI and ML, could provide valuable insights into the ecological and evolutionary responses of native species to IAS, allowing us to understand if and how these species adapt over time and how environmental conditions affect such interactions. Some limitations need to be overcome to fully take advantage of the potential of crittercams, biosensors, AI, and ML. Advances in battery life would enable prolonged studies (e.g. new ways of optimizing systems' power consumption while maintaining efficient wireless communications, self-charging systems for perpetual operations, or even self-powered sensor systems that harvest energy from the surrounding environment). Establishing remote networks across distinct habitats or large areas is needed to have a comprehensive view of IAS distribution, movements, behavior, and impacts, which demands investment and the development of new, better, and adapted solutions. In the case of crittercams, miniaturization would be essential as nowadays the available technology can only apply to larger animals. Lastly, and probably the biggest issue with this technology is the elevated price, which could impair its deployment at a large scale.

By providing real-time and specific biological data, biosensors can contribute to validating and refining models and predictions related to the species studied. Ground-truthing simulations involve validating SDMs or habitat suitability models, the information gathered by biosensors on the physiology, behavior, and location could confirm or refute the model's predictions (Lundy et al. 2012; Blecha and Alldredge 2015). On the other hand, the data retrieved can be used to refine environmental models and improve the accuracy of simulations related to species behavior and movement. Once again, regardless of the sensor used, these are extremely dependent on battery life and the availability of communicating stations. Previous studies already addressed the issue of battery life in real-time data transmission and suggested the use of algorithms based on accelerometer data to save battery when animals are inactive while capturing data with higher resolution when they are active (Brown et al. 2012; Kays and Wikelski 2023).

Biosensors have been applied to detect critical environmental situations such as pollution peaks, acting as early warning systems. For instance, by monitoring shell movement (i.e., closing time, changes in shell movement pattern, and changes in valve gape) it is possible to identify the type of stressor or contaminant that bivalves are exposed to, and trigger a warning signal (Kramer et al. 1989; Barile et al. 2016; Ferreira-Rodríguez et al. 2023). Following the same rationale, it could be possible to have sentinel species for IAS. For example, by understanding the changes in behavior in native species caused by IAS, real-time monitoring of these species could allow the early detection of IAS and accelerate eradication actions. However, this will demand experimentation to decipher the signals that are specific to the responses to IAS, which could be difficult as it might be impossible to distinguish it from the responses to other disturbances such as pollution or the presence of a native predator, among other possibilities. If such a distinction is possible, then we may couple the use of sensors with AI and ML to detect these patterns.

Conclusion

The technological developments in biosensors in the last two decades provide unprecedented possibilities in the field of biological invasions in freshwater ecosystems. There is a gap in the application of biosensors to study IAS between different taxonomic groups and bias towards telemetry-based sensors. This is probably caused by the difficulty to capture and adapt biosensors to organisms other than fishes. The potential data collected is also highly dependent on the sensor used, being unfit to serve studies on all IAS groups. Telemetry-based sensors are the most developed and used, it is thus necessary to invest in innovation and the development of other sensors more adapted to other taxonomic groups and goals.

Considering the described limitations that biosensors still have, efforts should be prioritized toward the miniaturization of the devices and the enhancement of battery life and real-time communication systems. The solutions developed should consider the type of study (i.e., species, environment, data, goals, invasion phase) conducted as they might be appropriate in certain cases but not in others. However, given the development of new technological frontiers, including AI, underwater internet, and the miniaturization of many devices, future opportunities to monitor and manage freshwater invasive species are insurmountable. Nonetheless, several caveats and biases are still to be overcome, which include the study of how environmental factors (e.g., turbidity, depth, salinity) and species characteristics (e.g. size) can impair the efficacy of biosensors.

Furthermore, the information gathered on a species in one region may not be applied to another since the species might change its behavior to adapt to different environmental conditions. Thus, increasing the number of studies on IAS using these technologies will increase access to quality data and provide highly reliable and integrative information that can enhance efficiency in the identification and application of appropriate management approaches. Making these data available in a global and open-access platform would also facilitate the comparison of information, methods, and success rates that could be helpful for different scientific and management entities. Given the quantity of information needed this demands a large amount of storage capacity, but considering the importance and economic impacts of freshwater IAS such investment would be invaluable.

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References

Alford RA, Brown, GP, Schwarzkopf L, Phillips BL, Shine R. (2009) Comparisons through time and space suggest the rapid evolution of dispersal behavior in an invasive species. Wildlife Research 36: 23-28. https://doi.org/10.1071/WR08021.

Allaire JJ, Gandrud C, Russell K, Yetman CJ (2017) networkD3: D3 JavaScript network graphs from R. R package version 0.4. https://cran.r-project.org/web/packages/networkD3/index.html.

Allen HJ, Waller WT, Acevedo MF, Morgan EL, Dickson KL, Kennedy JH (1996) A minimally invasive technique to monitor valve-movement behavior in bivalves. Environmental technology 17: 501-507. https://doi.org/10.1080/09593331708616411.

Alós J, Aarestrup K, Abecasis D, Afonso P, Alonso-Fernandez A, Aspillaga E, Barcelo-Serra M, Bolland J, Cabanellas-Reboredo M, Lennox R, McGill R, Özgül A, Reubens J, Villegas-Ríos D (2022) Toward a decade of ocean science for sustainable development through acoustic animal tracking. Global Change Biology 28: 5630-5653. https://doi.org/10.1111/gcb.16343.

Bajer PG, Chizinski CJ, Sorensen PW (2011) Using the Judas technique to locate and remove wintertime aggregations of invasive common carp. Fisheries Management and Ecology 18: 497-505. https://doi.org/10.1111/j.1365-2400.2011.00805.x.

Barile NB, Scopa M, Recchi S, Nerone E (2016) Biomonitoring of coastal marine waters subject to anthropogenic use: development and application of the biosensor Mosselmonitor®. Ovidius University Annals of Chemistry 27: 81-86. https://doi.org/10.1515/auoc-2016-0013.

Besson M, Alison J, Bjerge K, Gorochowski TE, Høye TT, Jucker T, Mann HMR, Clements CF (2022) Towards the fully automated monitoring of ecological communities. Ecology Letters 25: 2753-2775. https://doi.org/10.1111/ele.14123.

Bick CS, Lee I, Coote T, Haponski AE, Blaauw D, Foighil DÓ (2021) Millimeter-sized smart sensors reveal that a solar refuge protects tree snail Partula hyalina from extirpation. Communications Biology 4: 1-8. https://doi.org/10.1038/s42003-021-02124-y.

Blecha KA., Alldredge MW (2015) Improvements on GPS location cluster analysis for the prediction of large carnivore feeding activities: ground-truth detection probability and inclusion of activity sensor measures. PLoS One 10: e0138915. https://doi.org/10.1371/journal.pone.0138915.

Bopp JJ, Brenden TO, Faust MD, Vandergoot CS, Kraus RT, Roberts JJ, Nathan LR (2023) Drivers and timing of grass carp movement within the Sandusky River, Ohio: implications to potential spawning barrier response strategy. Biological Invasions 25: 2439-2459. https://doi.org/10.1038/s41598-020-62916-w.

Boulêtreau S, Carry L, Meyer E, Filloux D, Menchi O, Mataix V, Santoul F (2020) High predation of native sea lamprey during spawning migration. Scientific Reports 10: 1-9. https://doi.org/10.1038/s41598-020-62916-w.

Brown DD, LaPoint S, Kays R, Heidrich W, Kümmeth F, Wikelski M (2012) Accelerometer-informed GPS telemetry: Reducing the trade-off between resolution and longevity. Wildlife Society Bulletin 36: 139-146. https://doi.org/10.1002/wsb.111.

Brown GP, Phillips BL, Webb JK, Shine R (2006) Toad on the road: use of roads as dispersal corridors by cane toads (*Bufo marinus*) at an invasion front in tropical Australia. Biological Conservation 133: 88-94. https://doi.org/10.1016/j.biocon.2006.05.020.

Browning E, Bolton M, Owen E, Shoji A, Guilford T, Freeman R (2018) Predicting animal behaviour using deep learning: GPS data alone accurately predict diving in seabirds. Methods in Ecology and Evolution 9: 681-692. https://doi.org/10.1111/2041-210X.12926.

Cavallo B, Merz J, Setka J (2013) Effects of predator and flow manipulation on Chinook salmon (*Oncorhynchus tshawytscha*) survival in an imperiled estuary. Environmental Biology of Fishes 96: 393-403. https://doi.org/10.1007/s10641-012-9993-5.

Costa-Pereira R, Moll RJ, Jesmer BR, Jetz W (2022) Animal tracking moves community ecology: Opportunities and challenges. Journal of Animal Ecology 91: 1334-1344. https://doi.org/10.1111/1365-2656.13698.

Coulter AA, Bailey EJ, Keller D, Goforth RR (2016) Invasive Silver Carp movement patterns in the predominantly free-flowing Wabash River (Indiana, USA). Biological Invasions 18: 471-485. https://doi.org/10.1007/s10530-015-1020-2.

Couzin ID, Heins C (2022) Emerging technologies for behavioral research in changing environments. Trends in Ecology and Evolution 38: 346-354. https://doi.org/10.1016/j.tree.2022.11.008.

Cuthbert RN, Pattison Z, Taylor NG, Verbrugge L, Diagne C, Ahmed DA, Leroy B, Angulo E, Briski E, Capinha C, Catford JA, Dalu T, Essl F, Gozlan RE, Haubrock PJ, Kourantidou M, Kramer AM, Kourantidou M, Kramer AM, Renault D, Wasserman RJ, Courchamp F (2021) Global economic costs of aquatic invasive alien species. Science of the total environment 775: 145238. https://doi.org/10.1016/j.scitotenv.2021.145238.

Diagne C, Leroy B, Vaissière AC, Gozlan RE, Roiz D, Jarić I, Salles J, Bradshaw CJA, Courchamp F (2021) High and rising economic costs of biological invasions worldwide. Nature 592: 571-576. https://doi.org/10.1038/s41586-021-03405-6.

Donnelly RE, Caffrey JM, Tierney DM (1998) Movements of a bream (*Abramis brama* (L.)), rudd× bream hybrid, tench (*Tinca tinca* (L.)) and pike (*Esox lucius* (L.)) in an Irish canal habitat. Hydrobiologia 371: 305-308. https://doi.org/10.1023/A:1017083423786.

Elith J, Kearney M, Phillips S (2010) The art of modelling range-shifting species. Methods in ecology and evolution 1: 330-342. https://doi.org/10.1111/j.2041-210X.2010.00036.x.

Evans, T. G., Diamond, S. E., and Kelly, M. W. (2015). Mechanistic species distribution modelling as a link between physiology and conservation. Conservation physiology, 3: cov056. https://doi.org/10.1093/conphys/cov056.

Fahlman A, Aoki K, Bale G, Brijs J, Chon KH, Drummond CK, Føre M, Manteca X, McDonal BI, McKnight JC, Sakamoto KQ, Suzuki I, Rivero MJ, Ropert-Coudert Y, Wisniewska DM (2021) The new era of physio-logging and their grand challenges. Frontiers in physiology 12: 669158. https://doi.org/10.3389/fphys.2021.669158.

Ferreira-Rodríguez N, Beggel S, Geist J, Modesto V, Österling M, Riccardi N, Sousa R, Urbańska M (2023) Freshwater mussels as sentinels for safe drinking water supply in Europe. ACS ES&T Water 3: 3730-3735. https://doi.org/10.1021/acsestwater.3c00012.

Gallardo B, Clavero M, Sánchez MI, Vilà M (2016) Global ecological impacts of invasive species in aquatic ecosystems. Global change biology 22: 151-163. https://doi.org/10.1111/gcb.13004

Gallien L, Münkemüller T, Albert CH, Boulangeat I, Thuiller W (2010) Predicting potential distributions of invasive species: where to go from here?. Diversity and Distributions 16: 331-342. https://doi.org/10.1111/j.1472-4642.2010.00652.x.

Gherardi F, Tricarico E, Ilhéu M (2002) Movement patterns of an invasive crayfish, Procambarus clarkii, in a temporary stream of southern Portugal. Ethology Ecology and Evolution 14: 183-197. https://doi.org/10.1080/08927014.2002.9522739.

Goldbogen JA, Cade DE, Boersma AT, Calambokidis J, Kahane-Rapport SR, Segre PS, Stimpert AK, Friedlaender AS (2017) Using digital tags with integrated video and inertial sensors to study moving morphology and associated function in large aquatic vertebrates. The Anatomical Record 300: 1935-1941. https://doi.org/10.1002/ar.23650.

Guirado E, Tabik S, Rivas ML, Alcaraz-Segura D, Herrera F (2019) Whale counting in satellite and aerial images with deep learning. Scientific Reports 9: 14259. https://doi.org/10.1038/s41598-019-50795-9

Gurevitch J, Fox GA, Wardle GM, Taub D (2011) Emergent insights from the synthesis of conceptual frameworks for biological invasions. Ecology Letters, 14: 407-418. https://doi.org/10.1111/j.1461-0248.2011.01594.x.

Gussen CM, Diniz PS, Campos ML, Martins WA, Costa FM. Gois JN (2016) A survey of underwater wireless communication technologies. Journal Of Communication And Information Systems 31: 242-255. https://doi.org/10.14209/jcis.2016.22.

Gutiérrez JL, Jones CG, Sousa R (2014) Toward an integrated ecosystem perspective of invasive species impacts. Acta Oecologica 54: 131-138. https://doi.org/10.1016/j.actao.2013.10.003.

Haubrock PJ, Soto I, Ahmed DA, Ansari AR, Tarkan AS, Kurtul I, Macêdo RL, Lázaro-Lobo A, Toutain M, Parker B, Blonska D, Guareschi S, Cano-Barbacil C, Almela VD, Andreou D, Moyano J, Akalin S, Kaya C, Baycelebi E, Yoğurtçuoğlu B, Briski E, Aksu S, Emiroğlu Ö, Mammola S, De Santis V, Kourantidou M, Pincheira-Donoso D, Britton JR, Kouba A, Dolan EJ, Kirichenko NI, García-Berthou E, Renault D, Fernandez RD, Yapici S, Giannetto D, Nuñez MA, Hudgins EJ, Pergl J, Milardi M, Musolin DL, Cuthbert RN (2024) Biological invasions are a population-level rather than a species-level phenomenon. Global Change Biology 30: e17312. https://doi.org/10.1111/gcb.17312.

Hayden TA, Holbrook CM, Fielder DG, Vandergoot CS, Bergstedt RA, Dettmers JM, Krueger CC, Cooke, S. J. (2014). Acoustic telemetry reveals large-scale migration patterns of walleye in Lake Huron. PLoS One 9: e114833. https://doi.org/10.1371/journal.pone.0114833.

Hirsch PE, Fischer P (2008) Interactions between native juvenile burbot (*Lota lota*) and the invasive spinycheek crayfish (*Orconectes limosus*) in a large European lake. Canadian journal of fisheries and aquatic sciences 65: 2636-2643. https://doi.org/10.1139/F08-162.

Honda K, Arai T, Kobayashi S, Tsuda Y, Miyashita K (2012) Migratory patterns of exotic brown trout Salmo trutta in south-western Hokkaido, Japan, on the basis of otolith Sr: Ca ratios and acoustic telemetry. Journal of Fish Biology 80: 408-426. https://doi.org/10.1111/j.1095-8649.2011.03183.x.

Hounslow JL, Fossette S, Chong W, Bali R, Tucker AD, Whiting SD, Gleiss AC (2023) Behaviour-specific spatiotemporal patterns of habitat use by sea turtles revealed using biologging and supervised machine learning. Journal of Applied Ecology 60: 1828-1840. https://doi.org/10.1111/1365-2664.14438.

Jetz W, Tertitski G, Kays R, Mueller U, Wikelski M, Åkesson S, Rakhimberdiev E (2022) Biological Earth observation with animal sensors. Trends in ecology and evolution 37: 293-298. https://doi.org/10.1016/j.tree.2021.11.011.

Kadye WT, Booth AJ (2013) Movement patterns and habitat selection of invasive African sharptooth catfish. Journal of Zoology 289: 41-51. https://doi.org/10.1111/j.1469-7998.2012.00960.x.

Kao CC, Lin YS, Wu GD, Huang CJ (2017) A study of applications, challenges, and channel models on the Internet of Underwater Things. In 2017 International conference on applied system innovation (ICASI), Sapporo (Japan), May 2017. IEEE: 1375-1378. https://doi.org/10.1109/ICASI.2017.7988162.

Katzner TE, Arlettaz R (2020) Evaluating contributions of recent tracking-based animal movement ecology to conservation management. Frontiers in Ecology and Evolution 7: 519. https://doi.org/10.3389/fevo.2019.00519

Kays R, Wikelski M (2023) The Internet of Animals: what it is, what it could be. Trends in Ecology and Evolution 38: 859-869. https://doi.org/10.1016/j.tree.2023.04.007.

Kennedy PJ, Ford SM, Poidatz J, Thiéry D, Osborne JL (2018) Searching for nests of the invasive Asian hornet (Vespa velutina) using radio-telemetry. Communications biology 1: 88. https://doi.org/10.1038/s42003-018-0092-9.

Knight E, Hannah K, Foley G, Scott C, Brigham R, Bayne E (2017) Recommendations for acoustic recognizer performance assessment with application to five common automated signal recognition programs. Avian Conservation and Ecology 12: 14. https://doi.org/10.5751/ACE-01114-120214.

Kramer KJ, Jenner HA, de Zwart D (1989) The valve movement response of mussels: a tool in biological monitoring. Hydrobiologia 188: 433-443. https://doi.org/10.1007/BF00027811.

Lahoz-Monfort JJ, Magrath MJ (2021) A comprehensive overview of technologies for species and habitat monitoring and conservation. BioScience 71: 1038-1062. https://doi.org/10.1093/biosci/biab073.

Lennox RJ, Aarestrup K, Cooke SJ, Cowley PD, Deng ZD, Fisk AT, Harcourt RG, Heupel M, Hinch SG, Holland KN, Hussey NE, Iverson SJ, Kessel ST, Kocik JF, Lucas MC, Flemming JM, Nguyen VM, Stokesbury MJW, Vagle S, Vanderzwaag DL, Whoriskey FG, Young N (2017) Envisioning the future of aquatic animal tracking: Technology, science, and application. BioScience 67: 884–896. https://doi.org/10.1093/biosc i/bix098

Lennox RJ, Blouin-Demers G, Rous AM, Cooke SJ (2016) Tracking invasive animals with electronic tags to assess risks and develop management strategies. Biological invasions 18: 1219-1233. https://doi.org/10.1007/s10530-016-1071-z.

Lennox RJ, Dahlmo LS, Ford AT, Sortland LK, Vogel EF, Vollset KW (2023) Predation research with electronic tagging. Wildlife Biology 2023: e01045. https://doi.org/10.1002/wlb3.01045.

Lundy MG, Buckley DJ, Boston ES, Scott DD, Prodöhl PA, Marnell F, Teeling EC, Montgomery WI (2012) Behavioural context of multi-scale species distribution models assessed by radio-tracking. Basic and Applied Ecology 13: 188-195. https://doi.org/10.1016/j.baae.2011.12.003.

McClure EC, Sievers M, Brown CJ, Buelow CA, Ditria EM, Hayes MA, Pearson RM, Tulloch VJ D, Unsworth RKF, Connoll, RM (2020) Artificial intelligence meets citizen science to supercharge ecological monitoring. Patterns 1: 100109. https://doi.org/10.1016/j.patter.2020.100109.

Medina-Vogel G, Barros M, Organ JF, Bonesi L (2013) Coexistence between the southern river otter and the alien invasive N orth A merican mink in marine habitats of southern Chile. Journal of Zoology 290: 27-34. https://doi.org/10.1111/jzo.12010.

Mohsan SAH, Li Y, Sadiq M, Liang J, Khan MA (2023) Recent advances, future trends, applications and challenges of internet of underwater things (IoUT): a comprehensive review. Journal of Marine Science and Engineering 11: 124. https://doi.org/10.3390/jmse11010124.

Monceau K, Bonnard O, Thiéry D (2012) Chasing the queens of the alien predator of honeybees: A water drop in the invasiveness ocean. Open Journal of Ecology 2: 183-191. https://dx.doi.org/10.4236/oje.2012.24022.

Moser ML, Lindley ST (2007) Use of Washington estuaries by subadult and adult green sturgeon. Environmental Biology of Fishes 79: 243-253. https://doi.org/10.1007/s10641-006-9028-1.

Nath T, Mathis, A, Chen AC, Patel A, Bethge M, Mathis MW (2019) Using DeepLabCut for 3D markerless pose estimation across species and behaviors. Nature Protocols 14: 2152–2176. https://doi.org/10.1038/s41596-019-0176-0.

Norouzzadeh MS, Nguyen A, Kosmala M, Swanson A, Palmer MS, Packer C, Clune J (2018) Automatically identifying, counting, and describing wild animals in camera-trap images with deep learning. Proceedings of the National Academy of Sciences 115: E5716-E5725. https://doi.org/10.1073/pnas.1719367115.

Phillips BL, Brown GP, Webb JK, Shine R (2006) Invasion and the evolution of speed in toads. Nature 439: 803-803. https://doi.org/10.1038/439803a.

Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM, Kühn I, Liebhold AM, Mandrake NE, Meyerson LA, Pauchard A, Pergl J, Roy HE, Seebens H, van Kleunen M, Vilà M, Wingfield MJ, Richardson DM (2020) Scientists' warning on invasive alien species. Biological Reviews 95: 1511-1534. https://doi.org/10.1111/brv.12627.

Raby GD, Johnson TB, Kessel ST, Stewart TJ, Fisk AT (2020) Pop-off data storage tags reveal niche partitioning between native and non-native predators in a novel ecosystem. Journal of Applied Ecology 57: 181-191. https://doi.org/10.1111/1365-2664.13522.

Ricciardi A, Iacarella JC, Aldridge DC, Blackburn TM, Carlton JT, Catford JA, Dick JTA, Hulme PE, Jeschke JM, Liebhold AM, Lockwood JL, MacIsaac HJ, Meyerson LA, Pyšek P, Richardson DM, Ruiz GM, Simberloff D, Vilà M, Wardle DA (2021) Four priority areas to advance invasion science in the face of rapid environmental change. Environmental Reviews 29: 119-141. https://doi.org/10.1139/er-2020-0088.

Rutz C, Hays GC (2009) New frontiers in biologging science. Biology Letters 5: 289–292. https://doi.org/10.1098/rsbl.2009.0089.

Salamon J, Bello JP, Farnsworth A, Kelling S (2017) Fusing shallow and deep learning for bioacoustic bird species classification. In 2017 IEEE international conference on acoustics, speech and signal processing (ICASSP), New Orleans (USA), March 2017. IEEE: 141-145. https://doi.org/10.1109/ICASSP.2017.7952134.

Salo P, Nordström M, Thomson RL, Korpimäki E (2008) Risk induced by a native top predator reduces alien mink movements. Journal of Animal Ecology 77: 1092-1098. https://doi.org/10.1111/j.1365-2656.2008.01430.x.

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

Shihada B, Amin O, Bainbridge C, Jardak S, Alkhazragi O, Ng TK, Ooi B, Berumen M, Alouini MS (2020) Aqua-Fi: Delivering Internet underwater using wireless optical networks. IEEE Communications Magazine 58: 84-89. https://doi.org/10.1109/MCOM.001.2000009.

Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M, Pyšek P, Sousa R, Tabacchi E, Vilà M (2013) Impacts of biological invasions: what's what and the way forward. Trends in ecology and evolution 28: 58-66. https://doi.org/10.1016/j.tree.2012.07.013.

Sousa R, Gutiérrez JL, Aldridge DC (2009) Non-indigenous invasive bivalves as ecosystem engineers. Biological invasions 11: 2367-2385. https://doi.org/10.1007/s10530-009-9422-7.

Stakėnas S, Vilizzi L, Copp GH (2013) Habitat use, home range, movements and interactions of introduced Lepomis gibbosus and native *Salmo trutta* in a small stream of Southern England. Ecology of Freshwater Fish 22: 202-215. https://doi.org/10.1111/eff.12015.

Strandburg-Peshkin, A., Farine, D. R., Crofoot, M. C., and Couzin, I. D. (2017). Habitat and social factors shape individual decisions and emergent group structure during baboon collective movement. elife 6: e19505. https://doi.org/10.7554/eLife.19505.

Strayer DL (2010) Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. Freshwater Biology 55: 152-174. https://doi.org/10.1111/j.1365-2427.2009.02380.x.

Styrishave B, Bojsen BH, Witthøfft H, Andersen O (2007) Diurnal variations in physiology and behaviour of the noble crayfish *Astacus astacus* and the signal crayfish *Pacifastacus leniusculus*. Marine and Freshwater Behaviour and Physiology 40: 63-77. https://doi.org/10.1080/10236240701241538.

Tabak MA, Norouzzadeh MS, Wolfson DW, Sweeney SJ, VerCauteren KC, Snow NP, Halseth JM, Di Salvo PA, Lewis JS, White MD, Teton B, Beasley JC, Schlichting PE, Boughton RK, Wight B, Newkirk ES, Ivan JS, Odell EA, Brook RK, Lukacs PM, Moeller AK, Mandeville EG, Clune J, Miller RS (2019) Machine learning to classify animal species in camera trap images: Applications in ecology. Methods in Ecology and Evolution 10: 585-590. https://doi.org/10.1111/2041-210X.13120.

Wilson P, Thums M, Pattiaratchi C, Meekan M, Pendoley K, Fisher R, Whiting S (2018) Artificial light disrupts the nearshore dispersal of neonate flatback turtles *Natator depressus*. Marine Ecology Progress Series 600: 179-192. https://doi.org/10.3354/meps12649.