A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

NeoBiota 96: 211–236 (2024)
DOI: 10.3897/neobiota.96.128038

Review Article

Applications of biosensors in non-native freshwater species: a systematic review

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Abstract

Technological advances have boosted the ability to obtain large and high-quality ecological data. These new technological tools have the potential to rapidly develop knowledge on how species behave and interact in ecosystems at relevant spatial and temporal scales. Comprehensive time-series datasets on the in situ behaviour and dispersal of wild organisms are essential for addressing fundamental ecological and physiological questions regarding non-native freshwater species. In this review, we address how biosensors, hereby defined as a tool for electronic tagging and tracking, can be useful in assessing movement, internal states and behaviour in non-native freshwater species, plus information about the surrounding environment and discuss possibilities of future research.

We performed a systematic review of the available literature and retrieved a total of 132 scientific studies (from 1996 to 2023) detailing 140 examples of sensor use. Most studies used radio telemetry (40%; n = 53) followed by acoustic telemetry (34%; n = 45) and PIT telemetry (20%; n = 26) to study non-native freshwater 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). As expected, the number of studies noticeably increased since 2006, with the majority performed in North America (55%; n = 73), followed by Europe (30%; n = 40) and Oceania (7%; n = 9). Information provided by biosensors can be used to better understand the dynamics and impacts of cryptic non-native species and can be applied in the management of biological invasions.

We also addressed future directions concerning the use of biosensors in non-native freshwater 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 to provide information for management actions.

Key words: Biologger, biosensor, conservation, freshwater, invasive species, management, telemetry

OPEN ACCESS

Academic editor: Eric Larson
Received: 23 May 2024
Accepted: 10 October 2024
Published: 22 November 2024

Citation: Meira A, Carvalho F, Castro P, Sousa R (2024) Applications of biosensors in non-native freshwater species: a systematic review. NeoBiota 96: 211–236. https://doi.org/10.3897/neobiota.96.128038

Introduction

The introduction of non-native species has dramatically altered terrestrial and aquatic ecosystems and is now an important driver of biodiversity change, requiring 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 non-native species 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, from individuals to ecosystems (Sousa et al. 2009; Gutiérrez et al. 2014; Gallardo et al. 2016). Concurrently, non-native freshwater species can generate severe economic impacts, including biofouling of structures, changes in fisheries yields and management costs, amongst 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 these species (Strayer 2010). However, studying non-native species in the natural environment can be challenging, particularly for species that are cryptic, shy or avoid humans or for species that colonise habitats where direct observations can be difficult (Rutz and Hays 2009). The study of non-native species in freshwater ecosystems exemplifies some of these difficulties, where high turbidity, fast river flow and deep rivers and lakes, amongst others, may make the logistics and financial investment for in-situ studies highly demanding and unrealistic. Despite possible difficulties, managers and policy-makers would benefit from a better assessment of the basic ecological and physiological features of non-native species. This information will provide insights into fundamental ecological and evolutionary questions and 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 allowed the development of new tools, enabling us to gather larger amounts and higher-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 synchronises with depth and speed and the timing of mouth opening, maximum gape and mouth closure amongst other types of behaviour. In freshwater ecosystems, Hanssen et al. (2022) tagged Atlantic salmon (*Salmo salar*) smolts with a novel sensor tag to investigate mortality due to predation during the migration of smolts. These tools can also be useful to improve our understanding of the physiology, behaviour and ecology of non-native species and allow a more accurate assessment of ecological and economic impacts (Lennox et al. 2016, 2017, 2023; Katzner and Arlettaz 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 a determined non-native species on ecosystem functioning and dynamics. If multiple technologies can be integrated and contribute to open data, they can enable study of non-native species at different ecological levels that were previously mostly impossible.

New technological solutions are now increasingly available to better understand non-native species ecology and biosensors may be particularly useful (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 environmental variables, record sounds or images or take other remote measurements (Lahoz-Monfort and Magrath 2021). For example, Raby et al. (2020) used biosensors to compare the habitat use of the native lake trout (*Salvelinus namaycush*) and the non-native Chinook salmon (*Oncorhynchus tshawytscha*) and found both species to display different foraging tactics and behaviour, which allowed them to co-exist despite having similar diets. In the particular case of aquatic ecosystems, it should be noted that transmitters must be in the air to send data via satellite or GSM, but can send data from underwater to terrestrial fixed stations by radio or acoustic telemetry where the data are logged for later downloading; 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.

We reviewed the bibliography available concerning the use of biosensors in non-native freshwater species to assess: i) spatial-temporal patterns of published studies; ii) the breadth of the type of sensors used; iii) and most studied taxonomic groups. We also discussed and provided 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 including non-invasive sensors (i.e. sensors that do not impact species' physiology, behaviour or survival) and non-native species. While our search was conducted using Web of Knowledge (WoS) and different search bases may not cover the same publications, increasing bias, WoS provides various advantages (Falagas et al. 2008; Gusenbauer and Haddaway 2020). The search was based on an exhaustive compilation of search terms (See Suppl. material 1), including common terms (e.g. "biosensing", "invasive species", "non-native*") and specific terms for non-invasive sensors (e.g. "telemetry", "acoustic", "PIT*tag*"). We did not specify species names or genus to reduce bias. We searched only titles, keywords and abstracts and considered peer-reviewed studies discussing the use or using non-invasive sensors published up to 31 December 2023. However, only records reporting non-invasive sensors directly attached to the species' body, studies involving non-native 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) and function (i.e. what it had been used for) (Table 1). In addition, data on the geographic location (i.e. country and continent), the taxonomic group of the non-native 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 amongst 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, using QGIS (QGIS 2023) and included charts with the percentage of research on each taxonomic group.

Table 1. List of sensor types and function categories used in the retained studies.

Sensor type	Function
Acoustic telemetry	Behaviour
Radio telemetry	Interaction
PIT telemetry	Management
Hall sensor	Methodology
Heart sensor	Monitoring
HPV system	Physiology
Inductive proximity sensor	
Infrared sensor	
Micro acceleration data loggers	
Pop-off tags	
Pressure sensitive tags	
Thermal dissipation sensor	
Time-depth recorder	

General description of the dataset

After excluding records that did not match our criteria (i.e. studies not focusing on freshwater or riparian non-native species using non-invasive attached sensors), the final dataset comprised 132 scientific publications. These corresponded to 140 case studies since six publications used more than one sensor. The studies were mostly conducted in rivers (50%; n = 66), lakes (~ 27%; n = 35) and controlled freshwater environment (e.g. laboratory and mesocosms) (~ 8%; n = 11). A total of 14 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 sensitive tags, radio telemetry, thermal dissipation sensor, time-depth recorder and ultrasonic telemetry. Telemetry-based sensors that transmit data rather than log it on-board were the most well represented, accounting for 125 (~ 95%) studies (Fig. 1). These sensors were used to study non-native species behaviour, management, monitoring, biological interactions, physiology and survival, but also to develop methodologies to be used in future studies (Fig. 1). The majority of the 140 case studies (~ 72%; n = 101) focused on species behaviour (i.e. movement, habitat use, feeding habits and behavioural patterns), of which 18 reported a second function for the sensor (species management, n = 6; physiology, n = 5

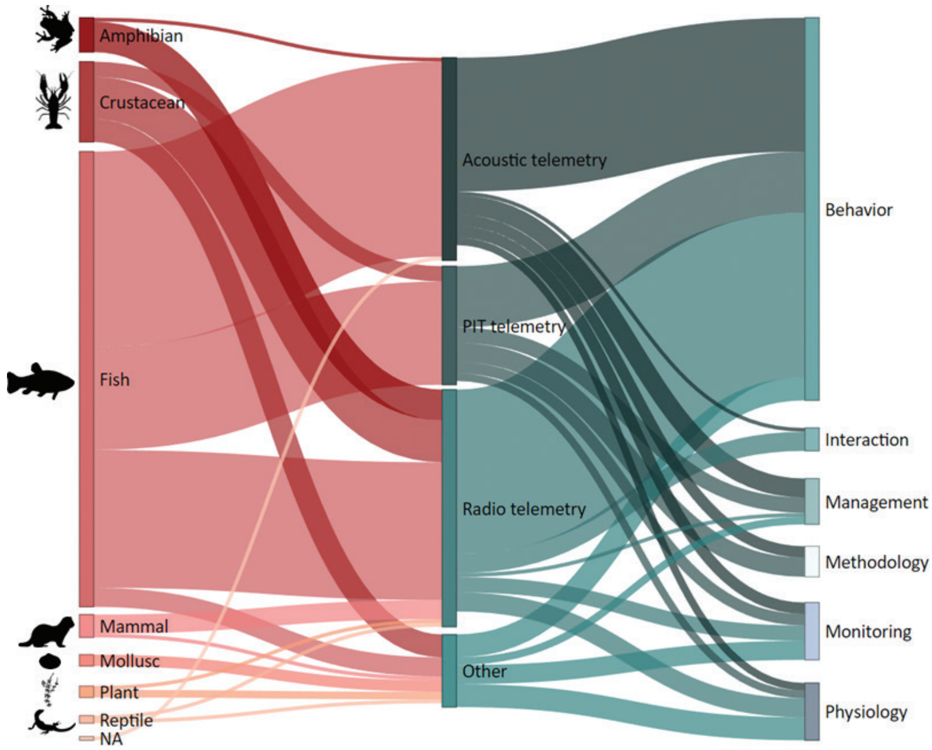

Figure 1. Linkage amongst the relative quantity of published records using biosensors for non-native freshwater species research by major taxonomic group, type of biosensors used and functions assessed. NA refers to the Chinook salmon (*Oncorhynchus tshawytscha*) which, despite being a native species, was used to assess the impacts of a non-native predator (see Cavallo et al. (2013)). The "Other" category includes hall sensor, heart sensor, HPV system, inductive proximity sensor, infrared sensor, micro acceleration data loggers, pop-off tags, pressure sensitive tags, thermal dissipation sensor, time-depth recorder and ultrasonic telemetry.

and monitoring, n = 4 and methodology, n = 2; and interactions with other species, n = 1). Non-native 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 three studies (~ 2%) and reptile (n = 2; ~2%) (Suppl. material 1). One paper (i.e. Cavallo et al. (2013)) studied the effects of a non-native predator by applying the sensor to the native fish species instead of the invader. The fish group included 32 non-native species, crustaceans included five, amphibians, molluscs, mammals and reptiles included only two each and plants included three (See Suppl. material 1). The most studied non-native 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* (n = 8; 5%, each).

Studies included in this review were conducted in 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 included 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 in non-native freshwater species were Canada and United Kingdom (n = 11; 8%, each), Australia (n = 9; ~ 7%, each) and the Czech Republic (n = 8; 6%). The other countries published four (~ 3%) or less studies.

Studies performed in North America focused mostly on non-native fishes (n = 73; ~ 76%; eight of the case studies used more than one species), which follow similar trends as reported in the general results (Fig. 2). Mammals were the only taxonomic group that was not studied in North America. European studies included fewer taxonomic groups, but were more evenly spread across taxa, with 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).

The number of studies generally increased over time, with the earliest published paper found in 1996 (i.e. Allen et al. (1996); Fig. 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) (i.e. 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, compared to two publications from Europe.

Studies from North America encompass a greater diversity of sensor types (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 seven 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

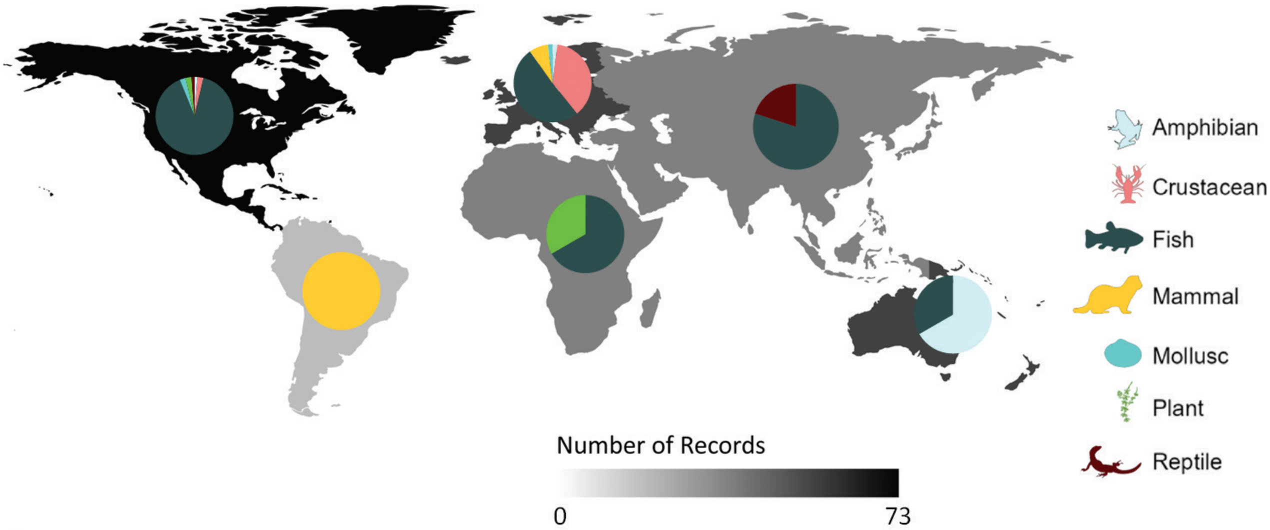

Figure 2. Geographic patterns of published studies using biosensors for aquatic non-native species research displayed by taxonomic groups.

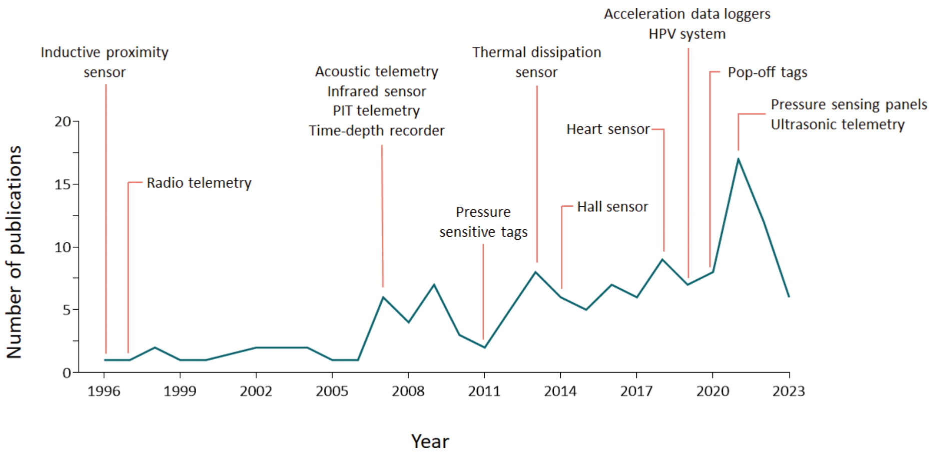

Figure 3. Number of publications per year on the use of biosensors to study non-native freshwater species. Milestones represent the first record of the use of each identified sensor in a non-native freshwater species.

(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.

As previously mentioned, species behaviour 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 behaviour 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%).

Considering the geographical distribution of the studies, some bias could be introduced and so some cautions need to be made when interpreting overall results. In fact, each country contains different environments and may be affected by different non-native species, thus displaying different priorities (Hulme et al. 2013). Consequently, this could result in focusing on different taxonomic groups as found in this review (Fig. 2) and using different biosensors, more adapted to countries' specific needs, creating an overall bias in our general results. On the other hand, the bias towards non-native fishes could be explained by this group being the most commonly introduced outside of its natural range for recreation and provisioning services (García-Berthou 2007).

Use of biosensors for studying non-native freshwater species

Acceleration data loggers

In general, accelerometers record acceleration forces in a continuous manner at a defined frequency or a defined time-average of the acceleration, being the data either stored or transmitted (Cooke et al. 2016). This type of sensor has been used to make empirical measurements of behaviour and energy expenditure mostly in terrestrial and semi-aquatic animals and fishes (Cooke et al. 2016). Acceleration Data Loggers provide detailed behavioural data, can operate in various environments, including underwater and allow long-term monitoring. However, they present limited battery life and require retrieval of the device for data analysis (Cooke et al. 2016).

Acceleration Data Loggers can be attached to non-native species to monitor their activity levels, swimming behaviour and movement patterns in their new environments (e.g. Whitney et al. (2021)). These data can help in understanding how these species interact with their surroundings, identify patterns in their invasiveness and assist in creating control strategies.

Acoustic telemetry

Acoustic telemetry involves attaching transmitters to animals that emit acoustic pulses. These signals are detected by receivers within the waterbody. The time and location of each detected pulse allow researchers to track the movements and behaviour of aquatic species, allowing to collect high-resolution data over long time periods (Hellström et al. 2022). This technology allows real-time tracking over large areas and provides precise location data (Hellström et al. 2022). It also presents some disadvantages, such as the need for a network of receivers, which can be expensive and complex to deploy and a limited range in shallow or obstructed waters. Additionally, transmitter size may limit use to larger species (Crossin et al. 2017).

Acoustic telemetry can be used to track the movement of non-native species within freshwater ecosystems, helping to map their distribution, dispersal patterns and habitat use (e.g. Stakėnas et al. (2009); Bopp et al. (2023)). This information can be crucial for managing and mitigating the spread of these species (Crossin et al. 2017; Hellström et al. 2022).

Hall sensors and inductive proximity sensors

Hall sensors are capable of detecting magnet-transducer paired magnetic field properties (Williams et al. 2020). When a magnetic object passes near the sensor, it produces a voltage proportional to the magnetic field strength. Inductive proximity sensors detect metal objects' presence without physical contact. They work by generating an electromagnetic field and detecting disturbances caused by the presence of metal within this field (Allen et al. 1996). These sensors can be used to measure position, speed and proximity. They have high sensitivity and accuracy and are durable and reliable in a myriad of environmental conditions, while displaying low power consumption. However, hall sensors require precise calibration and the detection range is limited (Ramsden 2011).

By attaching a magnet to an animal, hall sensors can quantify its amplitude, angular velocity and frequency of limb movements, providing insights into energy-saving mechanisms (Williams et al. 2020). Hall sensors and inductive proximity sensors can also measure respiration rates and extent of inhalation, heart rates, growth and even patterns of defecation, providing information on animal physiology and behaviour (e.g. Allen et al. (1996); Lorenz and Pusch (2013)).

Heart sensors

Heart sensors measure the heart rate of animals, typically using electrocardiography (ECG). These sensors are either implanted or attached to the animal to monitor cardiac activity in real-time (Cooke et al. 2004).

Heart sensors can provide insights into the physiological responses of non-native species to different environmental conditions, such as temperature changes, pollution levels or interactions with native species (e.g. Kuklina et al. (2018)). These data can help assess the stress levels and overall health of non-native populations.

Heat Pulse Velocity (HPV) Systems

HPV systems measure the speed at which heat pulses travel through plant stems, which correlates with sap flow and, by extension, water transport and transpiration rates. A heat pulse is introduced and sensors measure the time it takes for the heat to travel through the stem (Burgess et al. 2001). HPV systems provide precise data on plant water use, is non-destructive and can be used over time; however, it is limited to plant studies.

HPV systems could be used to study the water usage and transpiration rates of non-native freshwater plants and plants present in the riparian area, providing data on their impact on water resources in freshwater ecosystems (e.g. Mkunyana et al. (2019)). Understanding the water consumption of these species can help in managing water resources and controlling non-native plants.

Infrared sensors

Infrared sensors detect infrared radiation (heat) emitted by objects. These sensors can measure temperature or detect movement, based on changes in the infrared radiation patterns, but also measure heart rates (Styrishave et al. 2007). Thus, they are capable of detecting species in low-light conditions without requiring physical tagging, but are limited to detecting species with significant temperature contrast to the environment.

Infrared sensors could be used to monitor the presence, activity and physiology of non-native species, particularly in nocturnal or low-visibility conditions. They can also be applied to assess physiological responses (e.g. Styrishave et al. (2007); Berry and Breithaupt (2008)).

Passive Integrated Transponder telemetry

PIT (Passive Integrated Transponder) telemetry involves the use of small, implantable tags that emit a unique code when activated by a reader's electromagnetic field. These tags do not require a battery and are often used for tracking and identifying animals. Thus, PIT telemetry can provide individual identification of tagged animals, but requires close proximity to the reader for detection, being also limited to species that can be tagged.

PIT telemetry can be used to monitor the movement, growth and survival of non-native species in freshwater environments. By tagging individuals, researchers can gather long-term data on the population dynamics, habitat requirements and spread of non-native species (e.g. Lechelt et al. (2017); Dauphinais et al. (2018)).

Pop-off tags

Pop-off tags are data-logging devices that attach to an animal and are designed to detach at a predetermined time or under specific conditions. Once released, the tag floats to the surface, where it transmits its stored data via satellite (Block et al.

1998). These tags enable long-term tracking over large distances, the data can be recovered even if the animal is not recaptured and can provide detailed information about movement and collect large amounts of environmental data (Raby et al. 2020). However, they are relatively large, limiting use to larger species, often of single-use and require specific environmental conditions for data recovery (e.g. surfacing for satellite transmission).

Pop-off tags could be used to track the movements of non-native species over long distances or periods. Once the tag detaches, researchers can recover valuable data on the species' behaviour and habitat use, which is useful for understanding their spread and impact (e.g. Raby et al. (2020)).

Pressure sensitive tags

Pressure-sensitive tags measure the pressure exerted by the surrounding environment. These tags can provide data on depth and diving behaviour by recording pressure changes over time. They can also record environmental conditions, such as temperature and can be used on a wide range of species; however, these have to dive or change depth frequently (Filmalter et al. 2015).

Pressure-sensitive tags can be used to study the diving behaviour of non-native species in freshwater ecosystems (e.g. Bajer et al. (2011)). This information can help determine the habitat preferences and potential impacts of these species on native flora and fauna at different depths.

Radio telemetry

Radio telemetry involves attaching a transmitter to an animal which then emits radio signals. These signals are detected by a receiver, allowing researchers to track the animal's location and movement in real-time. This type of telemetry is effective for studying various environments and species, but have a limited range, requiring manual tracking and researchers to be relatively close to the tagged animal (Cagnacci et al. 2010; Gussen et al. 2016).

Radio telemetry can be used can be used to monitor the movement and distribution of non-native species in freshwater ecosystems (e.g. Sammons et al. (2003); Jones and Stuart (2009)). It is particularly useful for studying species in areas where GPS or acoustic telemetry is less effective, such as areas with dense vegetation or shallow waters.

Thermal dissipation sensor

Thermal dissipation sensors measure heat loss from a surface, often used in plant studies to determine transpiration rates. The sensor measures the temperature difference between a heated probe and its surroundings, which correlates with water movement and transpiration (Granier 1985). Similar to HPV systems it is non-destructive and can be used for long-term monitoring while being limited to plant studies.

Thermal dissipation sensors can be used to study the water use and transpiration of non-native freshwater plants (e.g. Moore and Owens (2012)). These data can help assess the impact of non-native species on water resources and ecosystem health in freshwater environments.

Time-depth recorder

Time-depth recorders (TDRs) log data on the depth and duration of an animal's dives over time. These devices are attached to the animal and record depth changes, allowing researchers to analyse diving behaviour and habitat use (e.g. Hays et al. (2007)). They are suitable for long-term studies and can be used on various non-native species, but like Pressure Sensitive Tags, they are limited to species that engage in diving behaviour.

Applications and their potential for management

Biosensors used to assess movement have the potential to provide information for population dynamics and support predictions on species dispersal at relevant spatial and temporal scales. Movement of non-native species can change with time, environmental conditions and position (i.e. individuals from the core and front of the invasion), such as in the well-known case of the invasive cane toad (*Bufo marinus*) (Phillips et al. 2006). The dispersal of this non-native 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 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 non-native species 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; Sousa et al. 2024). It is also important to note the type of system invaded and the connectivity between systems as the dispersal of non-native species 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.

Non-native species 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 behaviour (i.e. moving away from or avoiding the same areas as other species or conspecifics). 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 behaviour 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 Fischer 2008). In another case study, Salo et al. (2008) followed the movement of the non-native semi-aquatic American mink (*Mustela vison*) by radio-tracking and found that predation risk by a native top predator, White-tailed sea eagle (*Haliaeetus albicilla*), reduced mink's swimming distances. These results suggest that this behavioural change may impair mink's feeding behaviour and ultimately reduce mink population growth, mitigating its negative impacts on the invaded ecosystems.

Predation of native species can also be assessed 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 non-native 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 on within 8 days after tagging, indicating the impacts the European catfish 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 of America, the movement of the non-native 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 autumn. The characteristics of the movement (i.e. movement rates, distance and 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. 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 non-native Grass carp (*Ctenopharyngodon idella*) and the native walleye (*Sander vitreus*). These assessments can assist the selection of optimal timing and locations to deploy barriers and effectively block the movement of Grass carp to new habitats without affecting the native walleye. Thus, biosensors can assist the management of non-native species by providing the information needed to apply specific and effective measures. Using non-invasive infrared sensors, Styrishave et al. (2007) found that, while both native spinycheek crayfish (*Astacus astacus*) and non-native Signal crayfish (*Pacifastacus leniusculus*) displayed a similar nocturnal behaviour, *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.

Given the high ecological and economic impacts mediated by non-native species 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 (Fig. 4).

Regarding prevention, the use of biosensors could give insights into the physiological tolerances of the species. For example, heart sensors have been used to record crayfish survival and recovery rates when exposed to freezing temperatures, providing insight into crayfish adaptability to different environmental conditions (Kuklina et al. 2022). These data could help generate more accurate species distribution models (SDMs) (i.e. mechanistic vs. correlative SDMs). These more accurate mechanistic models can be used to better predict areas more susceptible to invasion (Elith et al. 2010; Gallien et al. 2010; Evans et al. 2015), making this information helpful to implement prevention and early detection measures at finer spatial scales. In this scope, sensors can allow the identification of invasion fronts and this can support early detection of first invaders in particular areas. These data could be potentially useful to identify sites where traps and barriers might be deployed to effectively eradicate or at least control non-native species.

Managing the expansion of non-native species and assessing their impacts can be very laborious, expensive and inefficient. The Judas technique can be a reliable and efficient way to control and contain these invasions with cost-effective benefits compared to other ways such as fishing permits. Bajer et al. (2011) showed high removal rates (52–94%) of the common carp (*Cyprinus carpio*) from lakes in

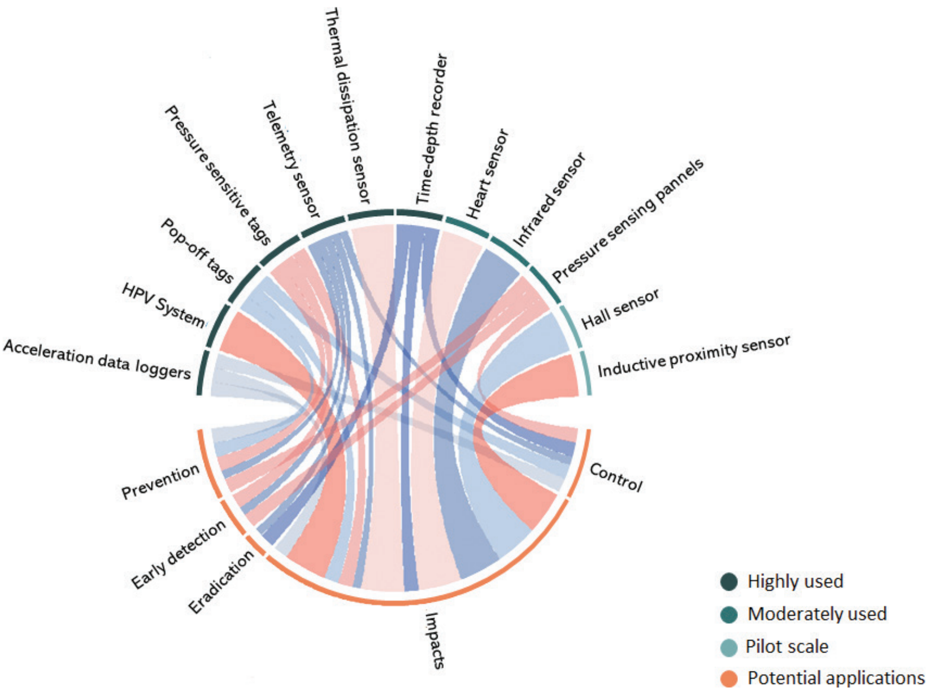

Figure 4. The level of development of biosensors identified throughout the studies included and their potential application in the management of non-native freshwater species. The level of development was classified, based on how much is known about the sensor, its user accessibility and how recurrent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

south-central Minnesota USA by using Judas fish that were radio-tagged coupled with pressure-sensitive tags, to locate winter aggregations of this non-native 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 spread of this non-native species. They have used radio telemetry to successfully detect the location of the nests, by attaching a 0.28 g 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 non-native freshwater species. In this section, we share our thoughts about 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.

The number of studies published on this topic decreased after 2021. Although it has not been apparent from the last two years, possibly due to the constraints caused by the Covid-19 pandemic, it is possible there will be a significant increase in the number of studies published in the future. Despite the limited number of studies using biosensors in non-native freshwater species research, the results of these studies suggest that the use of these tools could be beneficial to investigate how non-native species interact with other global stressors, such as climate change, habitat loss and fragmentation and pollution. For example: how warming may affect the behaviour and impacts mediated by non-native species, especially those species that are poikilothermic; how the presence of physical obstacles in rivers may affect the dispersal of non-native species; and how pollution or land use may influence the physiology and behaviour of non-native species. 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 non-native species. These assessments could contrast native and non-native species and determine if they respond differently to these human disturbances, which could provide information on the possible evolutionary advantages of non-native 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 amongst replicated pond environments.

There is a clear geographical bias in terms of number of publications using biosensors to investigate non-native freshwater species. As referred before, some regions are under-represented, this lack of research applying biosensors to investigate non-native freshwater species being possibly caused by a lack of investment (Pyšek et al. 2008; Hulme et al. 2013). Considering the importance of non-native species at the global scale and the usefulness of biosensors in this domain, the number of studies in these regions could be increased through international collaborations, funding initiatives in under-represented regions, such as through international collaborations, funding initiatives and capacity-building programmes.

Many biosensors have some combination of the following caveats that restrict their applications, such as size/weight influencing smaller species behaviour, 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. The current bias towards larger species found in the present review could be mitigated through the development of miniaturised sensors. Recent advancements will make this application possible for very small organisms without impairing their normal behaviour. 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. Moore and Brewer (2021) found that fishes tagged with micro-transponders (p-Chip) had higher survival than those tagged with traditional PIT tags, showing yet another advantage for the miniaturisation of sensors. Other non-invasive technologies could be applied to investigate smaller non-native species, such as environmental DNA (Barnes and Turner 2016; Brown et al. 2016); however, these methods are limited in terms of application for behavioural studies.

While some well-known and described examples of the use of biosensors in the control of invasive species exist, this type of application is only possible for the management of gregarious species or populations with low individual behavioural variability. For example, when using radio telemetry to assess the spatial behaviour of the invasive Red swamp 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 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 their being highly affected by propagation loss, which is conditioned by salinity and temperature, amongst 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 uses off-the-shelf components that reduce the cost of production, 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 optimise 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 providing information on non-native species 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 (McClure et al. 2020). Thus, the incorporation of AI tools in ultra-low power wireless integrated circuits 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 non-native species at a broader scale.

The use of animal-mounted cameras (crittercams) for identifying and monitoring non-native species 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 behaviour for the flatback turtle (*Natator depressus*), Hounslow et al. (2023) showed its potential for management and mitigation of threats by prioritising the protection of important specific behaviour locations (i.e. rest and forage). The same strategy could be applied to protect native from non-native species. 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 to non-native species, 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 optimising 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 non-native species distribution, movements, behaviour and impacts, which demands investment and the development of new, better and adapted solutions. In the case of crittercams, miniaturisation would be essential as currently the available technology can only apply to larger animals. Lastly and probably, the greatest 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, behaviour and location being used to 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 behaviour 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 non-native species. For example, by understanding the changes in behaviour in native species caused by non-native species, real-time monitoring could allow the early detection of non-native species and accelerate eradication actions. However, this will demand experimentation to decipher the signals that are specific to the responses to non-native species, 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, amongst 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 non-native species 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 non-native taxonomic groups. As 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 prioritised towards the miniaturisation 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) taking into account that they might be appropriate in certain cases, but not in others. However, given the development of new technologies, including AI, underwater internet and the miniaturisation of many devices, future opportunities to monitor and manage non-native freshwater species are numerous. 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.

Lastly, the creation of interdisciplinary working groups involving ecologists, engineers, data scientists and policy-makers could promote the development of biosensors more suitable and effective in their applications for ecological research, enabling efficient management of non-native freshwater species.

Acknowledgements

We thank the suggestions made by Robert J. Lennox and two anonymous reviewers, which improved the quality of our manuscript.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

This work was supported by the Portuguese Foundation for Science and Technology (FCT) and the European Social Fund through the North Portugal Regional Operational Programme through a doctoral grant to A. Meira (SFRH/BD/144570/2019). FCT also supported this research through national funds under the project MULTI-CRASH: Multi-dimensional ecological cascades triggered by an invasive species in pristine habitats (PTDC/CTA-AMB/0510/2021) (https://doi.org/10.54499/PTDC/CTA-AMB/0510/2021).

Author contributions

Conceptualization: AM, RS. Data curation: RS, PC, FC, AM. Formal analysis: AM. Funding acquisition: RS. Investigation: AM, RS, PC, FC. Methodology: FC, RS, AM, PC. Supervision: RS. Validation: RS, AM. Visualization: FC, AM. Writing - original draft: AM. Writing - review and editing: AM, RS, FC, PC.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Search strategy for ISI-Web of Knowledge database and the list of the invasive species studied with the use of biosensors and respective references

Authors: Alexandra Meira

Data type: docx

Explanation note: This list compiles all of the retained research papers used in this review.

Link: https://doi.org/10.3897/neobiota.96.128038.suppl1