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Efficiency of aquatic PIT-tag telemetry, a powerful tool to improve monitoring and detection of marked individuals in pond environments

Clément Duret · Fabien Pille · Mathieu Denoël

Laboratory of Ecology and Conservation of Amphibians (LECA), Freshwater and OCeanic science Unit of reSearch (FOCUS), University of Liège, 4020 Liège, Belgium

Corresponding author

Clément Duret, Laboratory of Ecology and Conservation of Amphibians (LECA), Freshwater and OCeanic science Unit of reSearch (FOCUS), University of Liège (ULiege), 4020 Liège, Belgium.

Email: clement.duret@uliege.be

Orcid IDs:

Clément Duret: 0000-0002-5809-4826

Fabien Pille: 0000-0002-8931-0368

Mathieu Denoël: 0000-0002-3586-8323

Abstract

Identifying and tracking individuals across time are a prerequisite to uncover key traits of their ecology and behaviour. However, obtaining fine-grain individual data at multiple locations, especially in aquatic environments, is challenging due to trade-offs between time constraints and detection probabilities. Aquatic telemetry of passive integrated transponder (PIT)- tagged organisms has been proposed to cope with detectability issues, but its efficiency has not been tested in stagnant waters. This technology was evaluated in ponds by monitoring marsh frogs (*Pelophylax ridibundus*). Multivariate survival models were fitted to quantify the success of detection rates over detection times and across ponds characterized by different habitat features. An average detection rate of 81% was obtained in less than 18 minutes on average, whereas a maximum detection rate was achieved in almost a quarter of the surveys. The detection rates were lower in the deeper and larger ponds but increasing detection times improved detection probabilities. Altogether, these results show that PIT-tag telemetry is a powerful tool to survey aquatic organisms, such as pond-breeding amphibians. The generalization of the use of this monitoring technique in ponds can therefore encompass fine-grain analyses over numerous sites and fill the gap between studies at local and landscape scales.

Keywords Aquatic telemetry · Detection efficiency · Monitoring technique · Passive integrated transponders · PIT tagging · Pond-breeding amphibians

Introduction

The estimation of key life history traits, such as survival rate and dispersal, is essential to understand the ecology of organisms and to apply efficient conservation measures (Pradel, 1996; Williams et al., 2002; Schaub et al., 2004; Petit & Valiere, 2006; Sinsch et al., 2012; Pittman et al., 2014; Unglaub et al., 2021). This estimation typically relies on successive captures of individually identified organisms. A wide range of marking and monitoring techniques have been developed for this purpose (Witmer, 2005; Silvy, 2020). While mid- and long-range techniques, such as very high frequency (VHF) and global positioning system (GPS), provide fine-grain results, they cannot be used on a large number of individuals or are limited by the battery and memory capacities (Girard et al., 2006; Hebblewhite & Haydon, 2010). Other techniques involving smaller marks typically require catching organisms repeatedly across time and therefore require a considerable investment of resources and time (Witmer, 2005). An exception is visual identification, but this technique can be impeded when animals are hidden under shelters or in aquatic environments. As a consequence, detection rates can be low, which may limit the possibility of complex statistical modelling, which is data hungry (Denoël et al., 2018; Cayuela et al., 2020), as well as the number of locations that can be studied during the same period of time (Kendall et al., 1995; Willson et al., 2011). Therefore, a challenging objective is to implement monitoring techniques that are able to provide the best recapture rates possible in a reduced period of time.

Radio-frequency identification (RFID) technology is of interest because electronic microchips using this technology (i.e., passive integrated transponder tags or PIT tags) do not require batteries or maintenance (Roberts, 2006; Want, 2006) and can be miniaturized. In ecology, these were first applied to fish (Prentice & Park, 1983) and then widely used to mark a plethora of taxa, including aquatic species, such as amphibians, for their identification and monitoring (Lucas & Baras, 2000; Roussel et al., 2000; Perret & Joly, 2002; Gibbons & Andrews, 2004; Schulte et al., 2007; Ferner, 2010; Testud et al., 2019). Several studies have concluded that this method has no detrimental effects on survival, growth, or body condition (Brown, 1997; Jehle & Hödl, 1998; Ott & Scott, 1999; Perret & Joly, 2002; Renet et al., 2021). The use of PIT tags allowed innovative investigations into numerous disciplines, including ecology, ethology, physiology, and biological conservation (Delcourt et al., 2018). Although seen initially as expensive, PIT tagging became affordable compared with other technologies (Cooke et al., 2004; Gibbons & Andrews, 2004), permitting long-term tracking of individuals (Arntzen et al., 2003).

Most research on PIT-tagged individuals involves capturing to read the tag with a handheld reader. Different solutions were subsequently developed to favor remote detection, which means using PIT telemetry. The most common system relies on fixed antenna that detects animal crossing, both on land or in running water. This latter system was particularly designed for fish crossing dams or sections of rivers (Pearson et al., 2016; Dzul et al., 2021). The use of remote detection with a mobile antenna was also developed recently, allowing the location of PIT-tagged animals, especially in shallow waters (Cooke et al., 2013). Such mobile PIT telemetry could be helpful to locate and identify individuals that alternate quickly between different environments, which is essential for setting up conservation tools (Semlitsch, 2008;

Hamer & Mahony, 2010; Joly, 2019) and for a fine-grain understanding of dispersal behavior (Denoël et al., 2018) and migration patterns between breeding and non-breeding sites (Sinsch, 1990; Semlitsch, 2008; Madison et al., 2010; Ousterhout & Semlitsch, 2014). Furthermore, as PIT tags can be detected at some distance from the receiver without manipulation of marked individuals, it could save time in the field.

The detection efficiency of PIT tags can vary according to tag size (Burnett et al., 2013), species behavior (Cucherousset et al., 2010), the type of antennas used (i.e., portable antenna versus pass-through detection system), and environmental factors (Hill et al., 2006; Banish et al., 2016; Zentner et al., 2021). A large proportion of studies testing the efficiency of PIT tags were based on fish in streams. The few studies dealing with the detection efficiency of PIT-tagged amphibians (Christy, 1996) tracked either stream water species (Cucherousset et al., 2008, 2010; Canessa et al., 2012; Kelly et al., 2017; Hammond et al., 2020; Zentner et al., 2021) or individuals during their terrestrial stage (Blomquist et al., 2008; Connette & Semlitsch, 2012; Ousterhout & Semlitsch, 2014; Ryan et al., 2014, 2015), but none in stagnant waters. More generally, the relation between detection rate, detection time, and environmental factors has never been specifically studied.

The purpose of this study was to determine the possibility and efficiency of mobile PIT telemetry in pond environments using PIT-tagged marsh frogs (*Pelophylax ridibundus*) as a representative species with strong aquatic habits and the most widespread anuran family at a world scale, the Ranidae. More specifically, the objectives were to determine the trade-off between detection rates and detection times across environmental contexts and to provide key points to improve detection rates. Detection rates correspond here to the proportions of marked frogs present in ponds that are detected by PIT telemetry. To do this, the efficiency of PIT telemetry was calculated considering the different habitat features of the ponds studied and the detection time. The main assumptions were (1) that high detection rates would be obtained in short periods of time with PIT telemetry, (2) that some habitat features, particularly deep and large ponds, would reduce the detection rate, and (3) that this issue could be alleviated by small increases in detection times.

Methods

Study model and study sites

The study took place in 19 ponds on the Larzac plateau (Hérault, France; between 43°48'N and 43°54'N and 3°21'E and 3°33'E). All studied ponds were colonized by marsh frogs (*Pelophylax ridibundus*) which are invasive in the area historically devoid of native *Pelophylax* species. The taxonomic status of marsh frogs in the studied sites was confirmed by molecular markers (Dufresnes et al., 2017; Pille et al., 2021). Larzac is a traditionally managed agricultural area where ponds are primarily used to water cattle (Durand-Tullou, 1959). The mean ± SE distance between the studied ponds was 1107 ± 160 m. The sites included eight natural ponds and 11 artificial ponds. Artificial ponds, locally named "*lavognes*", differ from natural ones by having a built substrate, typically of concrete. The mean ± SE water depth and surface area of ponds at the time of sampling were 98.8 ± 5.3 cm and 92.6 ± 28.5 m^2, respectively. To establish categories of equal sample size for both water depth and surface area, median values were selected. Ponds were classified into two water depth categories (shallow ponds with a depth of ≤ 96 cm and deep ponds with a depth of > 96 cm) and two surface areas categories (small ponds with a surface area ≤ 116 m^2 and large ponds with a surface area > 116 m^2).

Experimental procedures

Marsh frogs were caught in each pond by dip netting between April and July 2019. In total, 530 different adult individuals were tagged (mean ± SE: 15 ± 4 frogs per pond). Marking took place directly and close to the pond to immediately release the frogs at the place of capture. Each adult individual was tagged by inserting a 12-mm PIT tag (100 mg) under the skin of the back (Biolog-ID, 134.2 KHz). The frogs had a minimum length of 50 mm and body mass over 5 g; this means that the tag mass was always less than 2% of the biomass of the frogs. In this condition, where the tag mass is below 5% of the mass of the frog, PIT tagging is recognised as an ethical method of marking amphibians (Aldridge & Brigham, 1988; Winandy & Denoël, 2011) and this procedure was approved by the Ethical Committee of the University of Liège.

The protocol to test PIT telemetry efficiency was replicated monthly during three sessions (from May to July) in the 19 ponds. As some ponds had a low sample size late in the season, the total analyzed sample consisted of 45 trials, consisting of up to three replicates within sites (mean ± SE: 2.37 ± 0.19) and up to 16 replicates between sites (mean ± SE: 15 ± 0.58; Supplementary Table S1). For each trial, the procedure was split into two successive visits to each pond per month. During the first visit, carried out in the evening, frogs were caught by dip netting and the PIT tag of the marked frogs was screened with a microchip handheld reader (Agrident APR 500 RFID reader). A PIT tag was implanted in the unmarked individuals captured. The frogs were placed in individual tanks filled with water from their ponds and released in the evening right after the procedure at their place of capture. The second visit took place the following day, during day time, to give the frogs time to reuse their aquatic microhabitats, but not enough to allow emigration. Water frogs, such as the marsh frog, are long-term residents and preliminary data suggest that they typically do not leave their site on such a short period of time (C. Duret & M. Denoël, pers. obs.). During this second visit, the frogs were detected using a submersible mobile antenna (Biomark BP Plus Portable antenna, Boise, Idaho, USA) connected to a Biomark HPR Plus reader. For the deepest ponds were central access was less easy, detection was also done from a dinghy. During each visit with the portable antenna, the reader automatically recorded the time of the first detection of each frog. Before each detection, a tour of the pond was made to make sure that all the frogs at the edge of the pond were effectively in water for detection with the portable antenna (frogs on the shoreline jumped into the water). The detection with the portable antenna was made exclusively in the water with the antenna submerged, while the handler was walking inside the pond and the antenna was always held in a horizontal position because the detection distance is higher when the antenna is parallel to the long axis of the PIT tag (Cucherousset et al., 2005; Ousterhout & Semlitsch, 2014). The maximum distance detection of the submersible portable antenna was tested in a water-filled tank, showing a reading distance of up to 42 cm under water. In the field, the total detection time and ID numbers of the PIT-tagged frogs detected were automatically stored in the HPR Plus reader and extracted after each detection (Biomark

Tag Manager, version 3.16.2.1). In addition, as soon as a PIT-tag was detected, the time spent detecting from the beginning of the detection was also recorded with reader.

Data analysis

Cox model and environmental factors

To test the effect of pond features (type: artificial vs natural, water depth, and surface area of ponds), a survival model was used. The advantage of survival models is to consider the censored observations of individuals that are not detected within the detection time period. Specifically, a mixed Cox model, also called a proportional hazards model (Cox, 1972; Cox & Oakes, 1984), was implemented to simultaneously evaluate the effect of several factors on the "survival state" of individuals; this state corresponded to the detection of individuals across detection times in the present study (captured at the first visit and detected with the submersible antenna the following visit = 1; captured at the first visit and not detected with the submersible antenna the following visit = 0). The Cox model included three explanatory fixed variables: the pond type (artificial vs natural), the water depth of the ponds (shallow vs deep), and the surface area of the ponds (small vs large). Sex was not included in the models as preliminary analyses showed similar high detection rates. Considering that each pond was visited several times during the study, the sites were included as a random variable in the model. The model was computed with the package coxme (Therneau & Therneau, 2015). The validity and goodness of fit of the Cox model were assessed by verifying that the proportional hazards (PH) assumption was constant over time for each of the covariates with fixed effects in the model. To do so, the scaled Schoenfeld residuals statistical tests (Dessai & Patil, 2019) were applied using the package survival (Therneau & Lumley, 2014). All analyses were carried out in program R, version 4.1.0. A table summarizing the dataset used to conduct the analyses is available as a Supplementary Information (Supplementary Table S1).

PIT telemetry efficiency curves

The Cox model was also used to characterize PIT telemetry efficiency. Survival curves (i.e., efficiency curves in this study) were implemented from the Cox model. The cumulative number of frogs detected in each pond during the detection time and the final proportion of PIT-tagged frogs captured during the first visit that were detected with the submersible antenna the following day (i.e., the detection rate) allowed for the characterization of the efficiency of the method. Four thresholds of detection rates were used for this purpose: 50, 60, 70, and 80%. Survival curves representing the accumulative proportions of detected frogs were implemented using the packages survminer and ggplot2 (Kassambara et al., 2017).

Three-dimensional (3D) linear regression plots, using the package plotly (Sievert, 2020), were computed to provide estimations of the detection time needed according to the water depth and surface area of the ponds.

Results

The mixed effects Cox model showed a significant effect of environmental variables on detections across time (Fig. 1; Table 1). The hazard ratio (HR), i.e., the effect size of the covariate on the detections, was < 1 for the pond type, suggesting that detection rate was slightly lower in natural ponds compared to artificial ponds, although the effect was not significant (likelihood-ratio test: $p = 0.277$). A small water depth and surface area allowed better detection rates with hazard ratios of 1.428 and 2.692, respectively, both with significant effects (water depth: likelihood-ratio test, $p = 0.001$; surface area: likelihood-ratio test, $p < 0.001$) (Table 1).

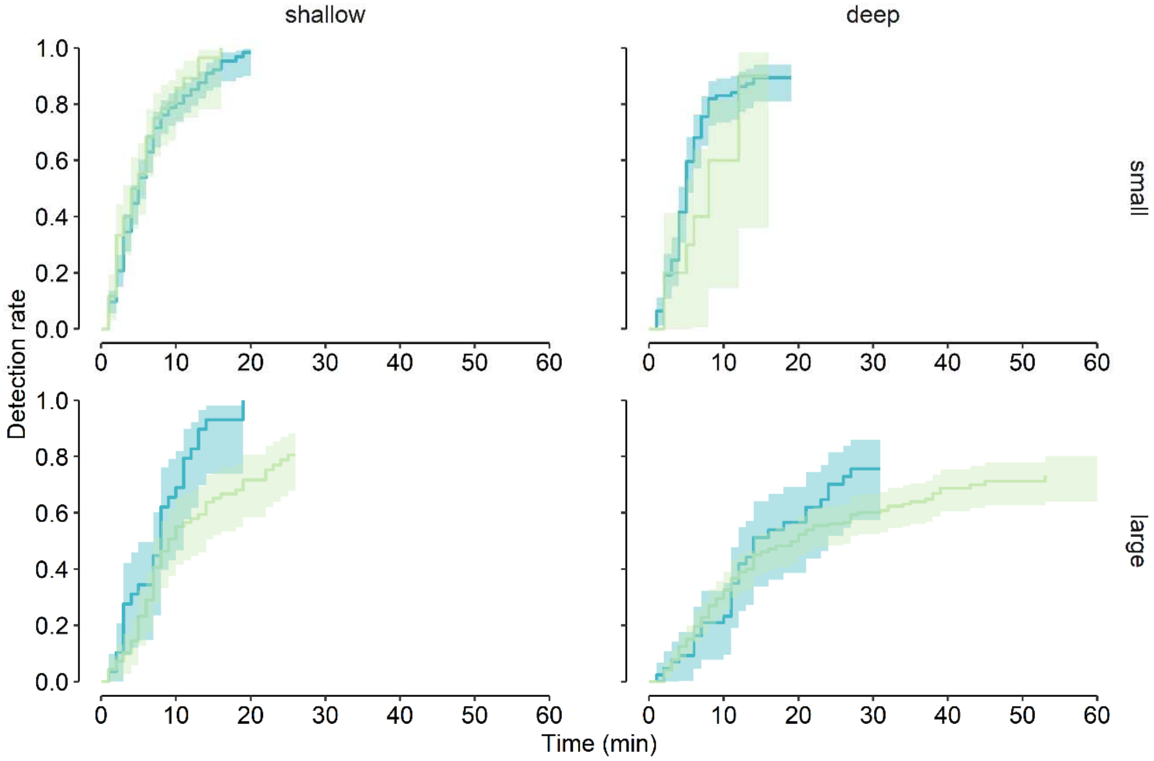


Fig 1 Detection curves fitted from the mixed effects Cox model according to pond features (small and large, shallow, and deep ponds). Blue: artificial ponds; green: natural ponds. The colored areas around each curve represent the 95% confidence intervals.

Table 1 Results of the mixed effects Cox model analysis. The hazard ratios (with SE and 95% confidence intervals) of each variable correspond to their size effect on the detection of marsh frogs. The *p* values were obtained from the likelihood-ratio tests.

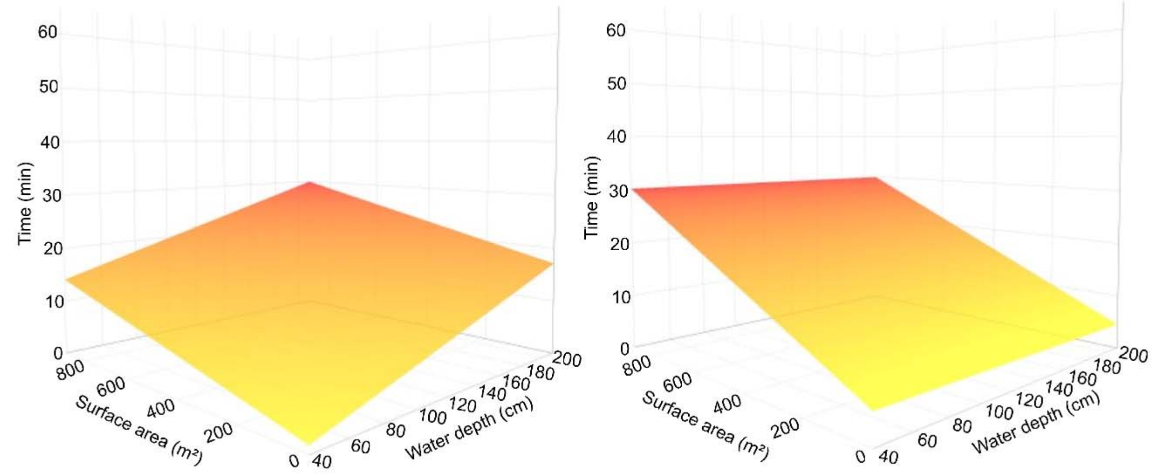
Variables	Hazard ratio (HR)	SE	95% CI	z	*p*
Pond type (natural)	0.798	0.207	0.532 - 1.198	-1.09	0.277
Depth (shallow)	1.428	0.109	1.152 - 1.769	3.26	0.001
Surface area (small)	2.692	0.179	1.895 - 3.825	5.53	< 0.001

The trade-off between detection rate and detection time varied across environmental contexts. Globally, a mean (± SE) detection rate of 81.40 ± 2.92% ($n = 45$) of the frogs present at ponds was obtained by aquatic telemetry for an effort of 17.38 ± 1.76 min of detection time. The detection rates and detection times for the four pond categories were, respectively, 62.98 ± 6.71% and 32.30 ± 4.32 min in deep and large ponds, 74.62 ± 9.26% and 13.29 ± 2.54 min in deep and small ponds, 79.34 ± 5% and 25.00 ± 3.89 min in shallow and large ponds, and 91.40 ± 2.41% and 11.08 ± 0.92 min in shallow and small ponds (Fig.1).

The three-dimensional plots illustrate the required detection times to achieve the specific targets of detection rates (Fig. 2). The equations incorporating detection time (Y, in min), water depth (a, in cm), and surface area (b, in m²) were $Y = -2.46 + 0.09a + 0.01b$, $Y = 5.03 + 0.03b$, $Y = 3.22 + 0.03a + 0.04b$, and $Y = 1.3 + 0.03a + 0.06b$ for obtaining detection rates of 50, 60, 70, and 80%, respectively.

(a) 50% detection rate

(b) 60% detection rate



(c) 70% detection rate

(d) 80% detection rate

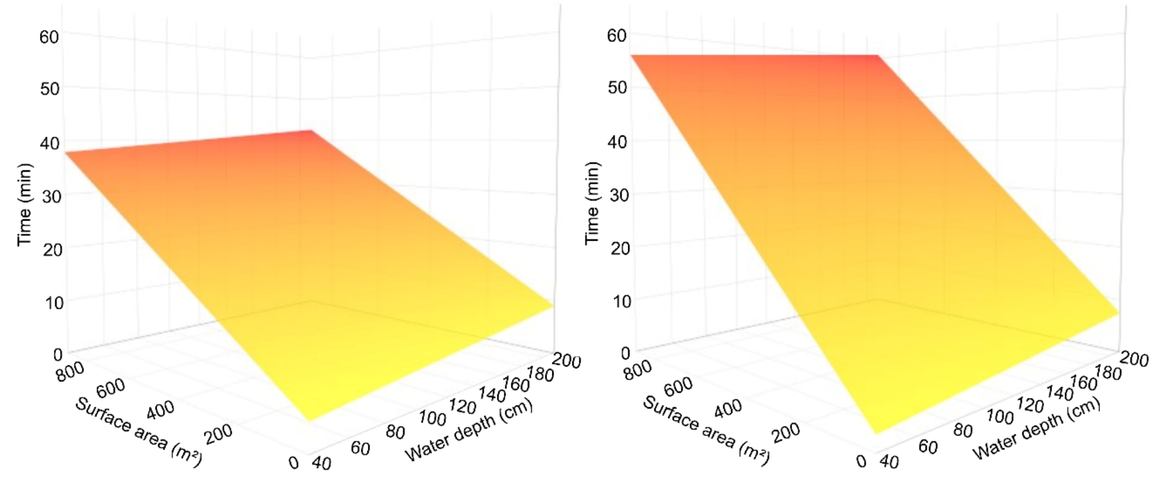


Fig 2 Three-dimensional representation of linear regressions of the estimated detection time needed to obtain (a) 50%, (b) 60%, (c) 70%, and (d) 80 % detection rates across ranges of water depth and surface areas. The warmer colors mean longer detection times.

Discussion

The results showed the high efficiency of underwater PIT telemetry in a repeated natural setting in pond environments. They are in line with research promoting the combined use of PIT tagging and telemetry to track individuals (Bubb et al., 2002; Hulbak et al., 2021; Saboret et al., 2021). The novelty lies in directly assessing detection rates to the known number of marked animals present in ponds and simultaneously encompassing the detection time and detectability, which showed that improving detection rates can be done in short time intervals. The analyses also highlight the importance of adapting detection times in the function of environmental context to maintain efficient detection probabilities.

Trade-offs between detection time and detection rates

The detection times needed to obtain satisfying detection rates are not well documented in the literature. The time investment for telemetry was previously studied with respect to the time needed to mark individuals with PIT tags. Roberts et al. (2021) showed that in a short time scale (one marking session), the handling time is higher with the PIT-tag technique than with photo-identification, but on a larger time scale (several years), the cumulative handling time becomes larger with the photo identification method. As a consequence, photo-identification and underwater telemetry each have advantages and the choice of methods would depend on habitat structure, species studied, and objectives. For instance, in habitats where detection rates need a long period of time due for instance to muddy waters, underwater telemetry could be the first choice.

Capture mark recapture models can estimate the probability of detection of marked individuals (Link, 2003; Bailey et al., 2004; Beranek et al., 2021), but this does not usually inform the effort of detection in terms of time spent at each studied site. Denoël et al. (2018) had average recapture rates of around 50% in pools using underwater telemetry tools as estimated by capture recapture models. This rate per se was already good and it was likely lower than in the present study because it included the non-recapture of animals that moved out of ponds, as time intervals between samplings were longer than in the present study. Thus, the recapture rates calculated in such studies do not specifically express the detection efficiency of the tracking methods. The trade-offs between detection time and detection rate are clearly highlighted in the results of the present study with the detection curves (Fig. 1). Detection rate is higher when the detection time is extended and high detection rates are achieved in a short time, but other factors influence the detection rate, especially environment features.

Integrating habitat features to improve detection rates

The influence of several environmental parameters on the detection efficiency of portable PIT telemetry was analyzed in previous studies, but all in lotic habitats and especially with fish species (Cucherousset et al., 2010; Banish et al., 2016; Zentner et al., 2021). Similar to the results in ponds from the present study, previous research in rivers showed that environmental complexity or the size of habitats can affect detection rates. For example, Banish et al. (2016) showed that percent boulder, large woody debris, and percent cobble have a negative impact on the detection in fish, whereas Connock et al. (2019) disclosed that the detection of giant salamanders can be reduced due to individuals hiding under large rocks. In this study, detection efficiency was reduced in the deepest and largest ponds due to the difficulty in detecting the deepest parts of the ponds and over larger surface areas, but it was not affected by the artificial versus natural structures of ponds. However, detections remained high in all configurations. Here, the results obtained showed that in shallow ponds with a relatively small area, the detection time needed to obtain 50% or 80% detection rates was very short. The small size of ponds and the ease of use of the telemetry technique save precious time in order to make it possible to survey a large number of ponds in a short time interval, which is a valuable advantage to implement capture recapture models. Such models, including environmental constraints, are in adequation with the results of the present study (i.e., obtaining good detection rates despite the environmental constraints in a short time interval), which means that habitat characteristics can be highly correlated with detection probability (Bailey et al., 2004). Time is also saved in PIT telemetry due to the non-invasiveness of the method; capture by hand or dip netting is not required to detect tagged animals. As a fast method, it involves a very short time at ponds with very high detection rates.

Limitations of underwater telemetry

Despite the high efficiency of the PIT telemetry shown in the present study, there are still limits to the extent that this technique can be used. As pointed out, the method was tested in typical ponds in a variety of dimensions, but in other regions, deeper ponds may prevent detection rates with a submersible antenna (Denoël et al., 2019). However, typical ponds and pools are often shallow and, in this case, can be surveyed by underwater telemetry. Underwater-fixed RFID antennas as used in rivers (Barbin Zydlewski et al., 2001; Pearson et al., 2016; Dzul et al., 2021) could provide an alternative option to mobile telemetry, but this may prevent the sampling of the entire ponds while representing a high economic investment. It may be useful for longitudinal fine-scale analyses of habitat use.

Using larger tag sizes improves detection rates (Burnett et al., 2013; Kelly et al., 2017; Delcourt et al., 2018), but using large tags is not possible in small-sized species or individuals. In the present study, 12-mm tags were used as a trade-off between the detection distance (max 42 cm) and the size of the frogs (mean size: 80 mm) to keep the correct ratio between the size of the frog and that of the tag. This tag size proved to be useful and previous research also showed that it did not disturb the behavior of amphibians (Winandy & Denoël, 2011). It is likely that smaller tags could only be easily detected in very small ponds, such as pools or puddles, and that tags as small as 7 mm and 0.33 g, also available on the market, would be recommended for underwater PIT telemetry in these habitats. In contrast, improvements in the power of detection using underwater antennas would broaden the use of smaller marks in aquatic telemetry.

Detecting the microchip of a tagged animal does not necessarily mean that the animal is present and alive, especially when the detection takes place in situations where the animal cannot be seen, such as in deep or muddy waters. This was not an issue in the present study as there was less than one day between the capture and detection of the frogs. Moreover, a special care was given to verify the movements of the detected frogs during telemetry. Long-term studies, which mean over several years, remain possible particularly when tracking long-lived organisms, but this involves the need to deal efficiently with the potential presence of dead individuals or lost tags if the detected individuals cannot be visually seen.

Perspectives in ecology and conservation

Whereas the benefits of using PIT tags for identification are largely documented in the literature (see e.g., Donnelly et al., 1994; Gibbons & Andrews, 2004; Ferner, 2010; Roberts et al., 2021), this study showed that combining it with underwater telemetry in ponds provides high detection rates without impacting field time. Therefore, this technology offers the possibility of broad-scale fine-grain surveys over a large number of aquatic habitats. Although capture mark recapture models were traditionally focused on a single habitat/population or a small set of population patches, recent research has shown the importance of replicating monitoring across multiple patches and geographic areas (Capellà-Marzo et al., 2020; Cayuela et al., 2021). This is particularly awaited, as conservation management needs to rely on precise and targeted guidelines that can emerge from capture mark recapture surveys across varied types of environments (Sinsch, 2014; Fernández de Larrea et al., 2021). Complex models are data hungry, also requiring high detection rates to better fit estimates of key variables, such as survival, fidelity, or dispersal. From this perspective, underwater PIT-tag telemetry is a powerful tool for quickly and efficiently monitoring aquatic and biphasic populations, such as those of pond-breeding amphibians. The generalization of this technique in complement with other marking and detection techniques when it is more suited would then provide the basis to depict new processes in ecology and conservation.

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Author Contributions:

Clément Duret contributed to conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing and preparation of original draft, and writing, reviewing, & editing of the manuscript. **Fabien Pille** contributed to data curation, investigation, methodology, and writing, reviewing, & editing of the manuscript. **Mathieu Denoël** contributed to conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, writing and preparation of original draft, and writing, reviewing, & editing of the manuscript.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest to declare.

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