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Upscaling behavioural studies to the field using acoustic telemetry

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ABSTRACT

Laboratory-based behavioural assays are often used in ecotoxicological studies to assess the environmental risk of aquatic contaminants. While results from such laboratory-based risk assessments may be difficult to extrapolate to natural environments, technological advancements over the past decade now make it possible to perform risk assessments through detailed studies of exposed individuals in natural settings. Acoustic telemetry is a technology to monitor movement and behaviour of aquatic organism in oceans, lakes, and rivers. The technology allows for tracking of multiple individuals simultaneously with very high temporal and spatial resolution, with the option to incorporate sensors to measure various physiological and environmental parameters. Although frequently used in fisheries research, aquatic ecotoxicology has been slow to adopt acoustic telemetry as a tool in field-based studies. This mini-review intends to introduce acoustic telemetry to aquatic ecotoxicologists, focusing on the potential of the technology to bridge the gap between laboratory assays and natural behaviours when making toxicological risk assessments.

1. Introduction

Animal behaviour is getting increasingly recognised as important in aquatic ecotoxicological research (as indicated by this special issue). Behavioural change induced by sub-lethal concentrations of chemicals can have far reaching detrimental consequences for the individual animal, and as a consequence potentially also for the population or ecological community (Dell'Omo, 2002). Important fitness-related behaviours, such as predator avoidance, locomotory performance, and feeding are increasingly being used as ecotoxicological endpoints and incorporated into risk assessments (Dell'Omo, 2002; Scott and Sloman, 2004; Brodin et al., 2014; Jonsson et al., 2014). The vast majority of all ecotoxicological behavioural studies are performed in controlled laboratory settings, even though many of them aim to assess the environmental risk of a certain chemical on ecological processes in large-scale, complex and dynamic natural systems (Newman, 2015). However, due to a mismatch in ecological complexity between laboratory systems and natural environments, the ecological relevance of laboratory-to-field extrapolations needs to be validated to increase the precision of ecotoxicological risk assessments (Klaminder et al., 2014). However, such validations are rarely done, and one reason for this is that that suitable methods to obtain reliable and high-quality in-situ data have been lacking (Little, 2002; Newman, 2015). Recently, advances in a technology called acoustic telemetry have enabled passive gathering of high-resolution behavioural data of free-ranging aquatic organisms in their natural environments. This technology has great potential to increase our understanding of how behavioural effects observed in the laboratory translate into ecological effects in the natural systems, and would allow for performing risk assessment of contaminants in natural settings, e.g. by generating field-based half maximal effective concentrations (EC_{50}). Acoustic telemetry could also function as an ecotoxicological monitoring tool of animals in polluted waters and provide data on when and where animals are at risk of being affected by chemical exposure, information that is highly useful in a management context. With this mini-review we aim to provide a basic introduction to acoustic telemetry for aquatic ecotoxicologists working both in the field and in the laboratory. First, we present a brief overview of the fundamentals of acoustic telemetry. Then, we provide an up-to-date synthesis of how acoustic telemetry has been used in ecotoxicology and adjacent research fields, with focus on quantification of animal behaviour, spatial (i.e. habitat) use, and survival. Finally, we end with a short prospect in which we highlight various powerful options that acoustic telemetry brings to aquatic ecotoxicology, not only as a tool to validate laboratory studies but also as a platform to study toxicological effects on highly complex ecological interactions and processes.

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2. Acoustic telemetry

At its core, acoustic telemetry is a technology to transfer information underwater using sound. An acoustic transmitter sends out information, e.g. an ID-code, as short tone-bursts, which are picked up, decoded, and timestamped by an acoustic receiver. As sounds propagate well under water, acoustic telemetry can be used to transfer relatively complex information over long distances and is hence well suited as a monitoring tool in aquatic research and management (Pincock et al., 2012). The use of acoustic telemetry involves attaching an acoustic transmitter (i.e. tagging) to an aquatic animal and using underwater receivers to collect information about that animal. Commonly, this information consists of presence, movement, and behaviour of the tagged animal, but it is also possible to retrieve data on its physiological status and surrounding environmental conditions through sensors incorporated into the transmitter (Cooke et al., 2004a). In studies using acoustic telemetry, fish is by far the most commonly studied group of animals, but the technique is also used to track species from a variety of taxa, such as lobsters and crabs (Comeau et al., 2012; Goldstein and Watson, 2015), crocodiles and alligators (Rosenblatt and Heithaus, 2011; Hanson et al., 2015), cuttlefish, squids and jellyfish (Downey et al., 2010; Moriarty et al., 2012; Bloor et al., 2013), sea stars (Chim and Tan, 2013), prawns (Taylor and Ko, 2011), toads (Letnic et al., 2014), as well as large marine mammals (Zeh et al., 2015).

In fish, the transmitter is usually implanted internally in the abdominal cavity by means of simple surgery, but depending on study objectives and environmental conditions the transmitter can also be attached externally, e.g. below the dorsal fin, or inserted into the stomach through the gastric tract (Liedtke and Rub, 2012). Fish are commonly anesthetized during the tagging procedure, and allowed to recover before being released. Tagging duration can vary from a few seconds to a few minutes depending on a variety of factors, such as the tagging method and the skill of the person tagging (Liedke and Rub, 2012). More complex transmitters with physiological sensors may take longer to implant and require more skill (Cooke et al., 2004a). With the advancement and miniaturization of batteries and microprocessors, transmitters are continuously decreasing in size and weight, and today fish as small as a few centimetres can be tagged and tracked (Brown et al., 2010; Deng et al., 2015). Transmitter life depends largely on the battery size and the delay time between emitted signals. Large transmitters (e.g. 80 × 16 mm, 10 g), suitable for fish like adult salmon or pike, can be active for many years with a delay time of one signal every other minute or so (Fig. 1). Smaller tags (e.g. 5 × 13 mm, 0.6 g) may transmit for several months even when sending data as frequently as every few seconds. Signal-delay time sets the temporal resolution of the data, and is decided by the user depending on study objectives. For example, to investigate multi-year spawning site fidelity in Atlantic cod (*Gadus morhua*), Zemeckis et al. (2014) tracked fish over four years using a large (98 mm) transmitter with a 1-minute signal transmission rate, whereas Johnston et al., 2004 (via Steigl and Holbrook 2012), studying the passage of juvenile salmonids through a hydropower turbine, positioned fish several times per second with new positions approximately every 8 cm of travel. In the latter example, the transmitters experienced significantly reduced battery life as a result of its small size and frequent signalling.

Although other technologies, such as radio- and PIT-tag telemetry, are also used to track aquatic animals in natural waters, acoustic telemetry is gaining momentum in both research and management through its ability to track aquatic organisms over large areas in different aquatic environments (oceans, estuaries, freshwaters), and the relatively ease at which fish can be positioned with high temporal and spatial resolution (Donaldson et al., 2014; Hussey et al., 2015). Today, commercial systems exist that allows for tracking of numerous fish simultaneously in near-continuous time with submeter or better spatial resolution in 2D or 3D (Cooke et al., 2005; McMichael et al., 2010). High-resolution positioning demands that a transmitter continuously can be detected by multiple receivers, which allows for triangulation of the position using the difference in signal arrival-time between receivers. To be able to position fish that move over larger areas, autonomous receivers are deployed in gridded networks spaced so that the detection ranges of the receivers overlap. Receivers can also be deployed at strategic locations, or along geographical lines, with the intent to only detect the presence of tagged fish somewhere within the detection range. Today, large receiver networks covering tens of km^3 are in use, as well as receiver lines reaching hundreds of km out into the ocean (Welch et al., 2009; Riley et al., 2014).

3. Acoustic telemetry as a tool in aquatic ecotoxicology

Although the majority of studies using acoustic telemetry has been descriptive in nature and skewed towards traditional fisheries management issues, the technology has recently started to be used in more hypothesis-based basic ecological and physiological research (Donaldson et al., 2014). Even though the potential for acoustic telemetry in aquatic ecotoxicology is apparent, surprisingly few studies to date have used this technology. Hence, in order to highlight the various options and possibilities that acoustic telemetry offer to the field, examples from other research areas have to be used. As exemplified below, several behavioural endpoints commonly measured in laboratory-based aquatic ecotoxicology can also readily be quantified with high resolution in free-ranging wild animals using acoustic telemetry, with the added benefit of having these endpoints quantified in the ecologically relevant context that laboratory-based studies are lacking.

As in most field-based ecotoxicological studies investigating behavioural responses, the way acoustically tagged animals are exposed to chemical substances will depend on study objectives. Behaviour of animals in polluted waters can be compared to animals in clean waters of similar size and structural complexity. A stronger approach would be to compare before and after data from two comparable lakes or ponds in which one of them have been intentionally polluted (spiked) midway through the study period. To avoid any environmental bias, animals can be pre-exposed to pollutants in the laboratory during a period before release into a lake or river, and their behaviour can then be compared to an unexposed control group being released simultaneously into the same water (e.g. Thorstad et al., 2012). Such a study design is expected to generate difference between treatments only during the period before the substance has been eliminated (i.e. excreted) from the exposed animal. Alternative methods of exposure could be to inject animals with the substance using exogenous implants (e.g. O'Tool et al., 2012), or potentially using implanted capsules (depositor) continuously releasing a precise amount of the chemical into the animal to counteract the elimination. The latter two methods would require the use of sham-treatments as control groups to avoid any potential effect of the injection procedure or capsule implants. Importantly, any study design including acoustic telemetry should ideally utilize the rigorous quality controls warranted for laboratory-based studies, including exposures to several quantified concentrations (in contrast to nominal concentrations) and repeated experimental runs (Harris and Sumpter, 2015).

4. Tracking spatial movements using acoustic telemetry

Acoustic telemetry is currently the best method available to gather individual-based high-resolution spatiotemporal data of aquatic habitat use over scales ranging from small ponds to large