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Synthesis

Where technology meets ecology: acoustic telemetry in contemporary Australian aquatic research and management

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Abstract. Acoustic telemetry is used to investigate a diverse suite of questions regarding the biology and ecology of a range of aquatic species, and is an important tool for fisheries and conversation management. Herein we present a brief review of the Australian acoustic telemetry literature in the context of key areas of progress, drawing from several recent studies and identifying areas for future progress. Acoustic telemetry has been increasingly used in Australia over the past decade. This has included substantial investment in a national acoustic array and the associated development of a national acoustic telemetry database that enables tag deployment and detection data to be shared among researchers (the Integrated Marine Observing System Animal Tracking Facility). Acoustic telemetry has contributed to important areas of management, including public safety, design and management of marine protected areas, the use of closures in fisheries management, informing environmental flow regimes and the impacts of fisheries enhancements, and is most powerful when used as a complementary tool. However, individual variability in movement often confounds our ability to draw general conclusions when attempting to characterise broad-scale patterns, and more work is required to address this issue. This overview provides insight into the important role that acoustic telemetry plays in the research and management of Australian aquatic ecosystems. Application of the technology transcends aquatic environments and bureaucracies, and the patterns revealed are relevant to many of the contemporary challenges facing decision makers with oversight of aquatic populations or ecosystems.

Additional keywords: acoustic tracking, conservation, fisheries management, freshwater, individuality, Integrated Marine Observing System, network, personality.

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Introduction

Acoustic telemetry is increasingly used to investigate diverse questions regarding the biology and ecology of fish, sharks, marine mammals, reptiles and invertebrates (Hussey *et al.* 2015). Quantifying and describing animal movements and space use at various scales is key to understanding the fundamental ecology of any aquatic organism, but is also essential for effective fisheries and conversation management (Cooke *et al.* 2016), and even public safety (McAuley *et al.* 2017). Acoustic tags were first deployed on aquatic animals around the middle of last century, with the position of tagged fish identified using echo-ranging systems (Trefethen 1956; Trefethen *et al.* 1957; Johnson 1960). Acoustic telemetry technology has rapidly developed over the past 20 years (Heupel *et al.* 2006), and the principles developed in these early tags laid the foundation for a burgeoning field of research that has offered remarkable insight into the life and habits of aquatic organisms in a range of environments (e.g. Hussey *et al.* 2015).

In recent years, major technological advances have increased both the quality of data obtained and the resolution of the patterns that can be observed. Some examples include the incorporation of acceleration sensors into acoustic transmitters (Payne *et al.* 2014), the miniaturisation of tags (e.g. Taylor and Ko 2011) and the development of positioning systems that can identify a tagged animal's position to sub-metre accuracy (e.g. Espinoza *et al.* 2011; Payne *et al.* 2015*a*). The combination of these technologies has produced some powerful studies linking behaviour, habitat and energetics and revealing the complex ecological interrelationships that govern resource use and decision making by aquatic animals (Payne *et al.* 2015*a*, 2015*b*; Brownscombe *et al.* 2017; Taylor *et al.* 2017*b*).

Acoustic telemetry is an important tool for Australian researchers studying aquatic animals. Earlier work in Australia used both sensor tags and conventional tags to address questions ranging from physiology to habitat use (e.g. McCosker 1987; Zeller 1997; Lowry and Suthers 1998), but the past decade has seen a substantial increase in the application of this technology (Fig. 1) and investment in associated infrastructure. This Special Issue of *Marine and Freshwater Research* presents a selection of Australian studies that highlight some recent biological and ecological insights gained through acoustic telemetry, as well as contemporary applications of this technology in fisheries and conservation management across freshwater, estuarine and marine ecosystems. In the context of the international literature, we also highlight the role of the Australian national network, present some novel combinations of acoustic telemetry technology with other approaches that further improve our insight into the ecology of aquatic animals, and discuss the implications of individual variation in movement patterns for management outcomes.

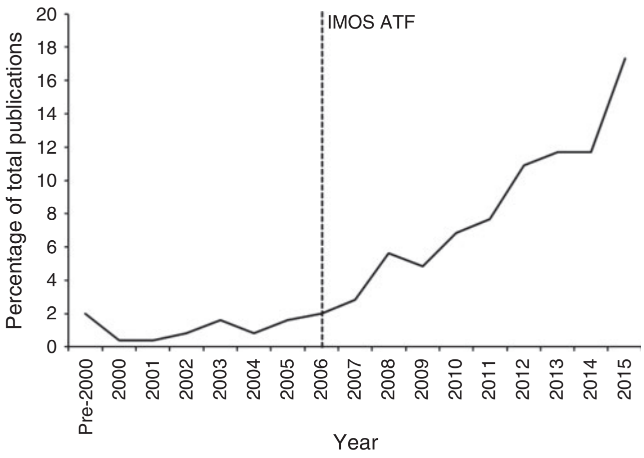

Fig. 1. Growth in Australian scientific publications using acoustic telemetry technology from 2000 to 2015. The data for each time point reflects the percentage of all Australian acoustic telemetry studies published within the period 2000–15 that were published in that particular year. Publication data were obtained from Web of Science, using the search terms 'acoustic telemetry', 'acoustic tracking', 'acoustic transmitter' or 'acoustic tag' (search results were refined for Australian publications in aquatic-oriented research categories). The advent of the Integrated Marine Observing System Animal Tracking Facility (IMOS ATF) in 2006 is indicated.

The national network: Integrated Marine Observing System Animal Tracking Facility

The Integrated Marine Observing System (IMOS) was established in 2006 and includes a broad suite of facilities that observe various attributes of Australia's coastal and open oceans (Hill *et al.* 2010). The IMOS Animal Tracking Facility (IMOS ATF; formerly known as the Australian Animal Tracking and Monitoring System, or AATAMS) represents the higher biological observing program nested within IMOS and includes an array of more than 570 permanent receiver stations, with additional detections submitted from another 1320 receiver stations operated by the broader IMOS ATF community. The development of IMOS ATF has occurred alongside the development of similar networks throughout the world (e.g. Cooke *et al.* 2011; Moustahfid *et al.* 2011; Daly *et al.* 2014; Block *et al.* 2016; Table 1), and has facilitated the storage and sharing of both tag and detection data among the majority of researchers using acoustic telemetry in estuarine and marine systems within Australia.

Although the development of continental-scale acoustic arrays (see Table 1) is thought to provide broad-scale benefits to users in an efficient manner, assessments of the efficacy of such arrays are lacking. In this Special Issue, Steckenreuter *et al.* (2017) present a novel quantitative analysis of the IMOS ATF array and identify the relative efficacy of stations within receiver curtains by considering the standardised number of detections per station, the standardised number of transmitters per station, and species occurrence. The analyses indicated that up to 53% of receiver stations could be excluded from curtains with minimal loss of information and that the overall national receiver network could be reduced by 36% while still retaining 84% of total detections, 86% of transmitters and 100% of detected species. The optimisation model used could readily be applied to other arrays to similarly evaluate their effectiveness, or assist in the rationalisation of such extensive acoustic networks.

The infrastructure deployed through the IMOS ATF has directly supported targeted studies for several species (e.g. Babcock *et al.* 2017; Oh *et al.* 2017; Pillans *et al.* 2017), but the benefits of the national array are not confined to the backbone infrastructure. The sharing of detection data among researchers has revealed novel movement patterns for many species. For example, tags deployed to study the movement patterns of fish associated with both estuarine (e.g. yellowfin bream, *Acanthopagrus australis*; Lowry *et al.* 2017) and offshore (e.g. Port Jackson shark, *Heterodontus portusjacksoni*; Keller *et al.* 2017) artificial reefs were detected on separate arrays owned by other projects deployed hundreds of kilometres away in far south-eastern Australia. The findings of the latter study were further refined by Bass *et al.* (2017), who showed that although both male and female sharks undertook similar migrations, each sex undertook their migration at different times. The potential for these species to undertake large-scale migrations was unexpected, and these patterns would not have been revealed were it not for the national network. Similar unexpected results were found for spangled emperor *Lethrinus nebulosus* (Babcock *et al.* 2017), whose migrations along Ningaloo reef would not have been detected without the backbone provided by the national IMOS ATF infrastructure. Finally, the most

Table 1. Summary of some major collaborative marine acoustic telemetry networks, showing geographic scale and key references describing the networks

Network name	Country	Geographic scale	Reference
Integrated Marine Observing System Animal Tracking Facility	Australia	National or continental	Steckenreuter *et al.* (2017)
Ocean Tracking Network (incorporating Pacific Ocean Shelf Tracking)	Canada	International	Cooke *et al.* (2011)
Animal Telemetry Network (incorporating several networks across the US)	USA	National	Block *et al.* (2016)
Lifewatch	Belgium	National	Reubens *et al.* (2016)
Acoustic Tracking Array Platform	South Africa	National	Daly *et al.* (2014)

extensive study of bull shark (*Carcharhinus leucas*) movements reported in Australia was made possible through the national network, and revealed complex inter-jurisdictional connectivity patterns along the east coast of Australia that have broad implications for the management of the species (Heupel *et al.* 2015).

Movement ecology in a management context

Australian researchers helped pioneer the application of acoustic technology for remote monitoring and transmission of tag detections (e.g. Vemco VR4 global receivers, Bedford, NS, Canada; Bradford *et al.* 2011). This technology has since seen widespread application in the real-time detection of potentially dangerous megafauna along the Australian coast, principally to help manage the risk of shark attacks along popular beaches. McAuley *et al.* (2017) provide a recent application of this technology to understand ecological drivers of white shark (*Carcharodon carcharias*) movements in a public safety context. This synthesis found little evidence of predictable movement patterns across broad scales, either in the location of animals, the direction of their migration or the timing of their movements; however, the data did suggest some predictable patterns in movement at smaller, regional scales (McAuley *et al.* 2017). The integration of this technology with both the national network and use of smartphone apps (see http://www.dpi.nsw.gov.au/fishing/sharks/sharksmart, accessed 15 May 2017) for notification have given the public unprecedented exposure to real-time animal movements in their own local context.

The study of fish movements and partitioning of space and time among different habitats is increasingly used to inform the design and management of marine protected areas across the continent. Studies demonstrating high site fidelity within marine parks reinforce the function of sanctuary zones in mediating exposure of exploited populations to fishing mortality, and recent examples include heavily targeted species such as luderick (*Girella tricuspidata*, Ferguson *et al.* 2013) and bluespotted flathead (*Platycephalus caeruleopunctatus*, Fetterplace *et al.* 2016). Acoustic telemetry technology has revealed annual return migrations of spangled emperor across the boundaries of no-take areas and over distances of more than 100 km. These are potentially spawning migrations, highlighting that spatial management needs to give regard to movement patterns that are important in a species' life history if depleted populations are to recover (Babcock *et al.* 2017). Studying shark movements has also revealed that no-take areas are an important management tool for effective protection of species of conservation concern, particularly during vulnerable juvenile stages (Oh *et al.* 2017). Spatial management is not limited to no-take areas and the importance of robust knowledge of species movements in fisheries management is exemplified by Fowler *et al.* (2017), who used telemetry to show that a long-term spawning closure was of limited effectiveness for snapper (*Chrysophrys auratus*) in the Gulf of St Vincent.

Quantitative data on fish movements and migration are equally important in determining the effect of measures aimed at fisheries enhancement (Ebner *et al.* 2007; Pursche *et al.* 2013; Taylor *et al.* 2017*a*). For example, artificial reefs are being deployed in most Australian jurisdictions, with a key focus on structures that incorporate specific design features that are of benefit to species of interest (e.g. Becker *et al.* 2017). Acoustic telemetry plays an important role in understanding how these structures function as a refuge, a source of food, a source of fishing mortality or combinations therein. In a multispecies study, Keller *et al.* (2017) show that artificial reefs with these design features may have a positive effect on fidelity to the structure, with tagged animals showing a greater affinity to the artificial reef than adjacent natural reefs that lacked vertical relief. Similar patterns were observed for an estuarine artificial reef by Lowry *et al.* (2017), and both these studies show clear patterns that reflect the importance of these reefs in mediating connectivity and dispersal. Much remains to be learned about the importance of individual behaviours in relation to isolated structures, whether they be artificial or natural, as seen in the fidelity of herbivorous grey drummer (*Kyphosus bigibbus*, Pillans *et al.* 2017) to adjacent patch reefs and the differences in foraging patterns exhibited by fish from these reefs. This was a surprising result given grey drummer home ranges are the largest recorded for a herbivorous reef fish.

Although acoustic telemetry technology has been applied most widely to marine and estuarine environments to date, it is playing an increasingly important role in the research and management of fish in freshwater habitats, many of which are threatened and of conservation concern. Limited knowledge of the ecological and environmental factors governing migration, connectivity and reproduction in freshwater and diadromous fish has hindered their management and conservation. However, over the past decade acoustic telemetry has revealed critical aspects of the life history and movement ecology of freshwater species in Australia, and this information is now being broadly incorporated into water resource policy and management (e.g. Reinfelds *et al.* 2010; Koster *et al.* 2017). Koster and Crook (2017) summarise information from telemetry studies for four Australian freshwater species of management interest to demonstrate how results from telemetry research can be integrated as conceptual models to support the development of environmental flow rules and other conservation measures. Harding *et al.* (2017) provide a good application of these principles in a practical sense, and show that the intersection of maturation and connectivity facilitated by high-flow conditions is essential for successful spawning migration in Australian bass (*Percalates novemaculeata*). Importantly, the ability to track fish has also allowed quantification of the magnitude of environmental flows required for successful spawning movements past weirs and dams. This, in turn, further highlights the need to consider species biology when designing environmental flow rules. Roberts *et al.* (2017) present a lacustrine example of the application of acoustic telemetry for understanding the consequences of changes in freshwater flow and their effects on habitat quality in a species with complex behavioural traits, namely the Australian lungfish (*Neoceratodus forsteri*). Given that the delivery of environmental flows is one of the most important management challenges in Australian freshwater systems, these studies provide a timely demonstration of how acoustic telemetry data can be used to ensure that water releases are managed optimally to meet the ecological requirements of the species they are intended to benefit.

Power of complementary approaches

Several recent examples have demonstrated the power of acoustic telemetry in resolving the drivers of animal movement when the information is incorporated with other complementary data sources (e.g. Payne *et al.* 2015*a*). Matley *et al.* (2017) combine acoustic telemetry data with stable isotope analysis to interpret movement patterns in the context of dietary overlap for two co-occurring *Plectropomus* spp. The patterns resolved indicated that spatial partitioning of foraging habitat between species was likely driven by interspecific competition arising from similar trophic niches. Crook *et al.* (2017) combined acoustic telemetry with otolith chemistry and aging analysis to understand size- and stage-specific migrations in barramundi (*Lates calcarifer*). The telemetry data revealed extensive movement during the wet season, with many fish homing to dry season refuges as floodwaters receded; the otolith analyses provided age-specific information on individual salinity histories across the whole life history. Integration of this information led to the proposal of an alternative life history model for the species, which described three distinct migratory contingents. These examples provide an insight into the potential for improved interpretation of movement patterns when other complementary data are collected, and investigators are encouraged to consider this in the design of future studies.

Confounding effects of fish 'personality'

It is becoming increasingly clear that there is a need to better understand behavioural variations within species. This is important if we are to understand the ecology and evolution of fish and sharks, and if we are to manage them successfully. Many of the studies described above comment on the high levels of variation in behaviour among individuals, or present data that clearly show the high level of individual variation in behaviour relative to other sources of variation in home range, habitat use and migration (Babcock *et al.* 2017; Fowler *et al.* 2017; Keller *et al.* 2017; Oh *et al.* 2017; Roberts *et al.* 2017). Individual variation in behaviour and fish 'personalities' have been recognised for some time (e.g. Tyler and Rose 1994). However, despite the implications of such variability for understanding ecological and evolutionary processes, and in comparative studies (Bolnick *et al.* 2003), this largely remains a topic that is noted incidentally in the context of other sources of variation. This leads us to ponder what is the ecological niche of a species when the range of that niche is encompassed almost entirely by individual variation (e.g. Smith *et al.* 2011)?

Individual variation has important implications for both fisheries management (Tyler and Rose 1994) and conservation (Parsons *et al.* 2010; Babcock *et al.* 2017), and new methodologies and analytical approaches may be needed to adequately describe such variation (Bolnick *et al.* 2003). Although we have made significant progress in developing the technologies and methodologies to measure individual movements and behaviour, much more remains to be done to understand and quantify the implications and emergent consequences of these individual behaviours at the population level. For example, home ranges of fish may suggest they are protected within no-take areas, but modelling in a population context including levels of residency and migration allows a quantification of effectiveness, indicating protection is partial at best (Babcock *et al.* 2012; Knip *et al.* 2012). Similarly, there is great potential to more broadly apply quantitative methods to telemetry detection data to provide estimates of mortality (Heupel and Simpfendorfer 2002; Welch *et al.* 2009; Topping and Szedlmayer 2013), particularly in the context of open-access databases, such as that of the IMOS ATF, which holds tens of millions of detections.

Conclusion

This overview provides an insight into the important role that acoustic telemetry plays in the research and management of Australian aquatic ecosystems. Application of the technology transcends aquatic environments and bureaucracies, and the patterns revealed are relevant to many of the contemporary challenges facing decision makers with oversight of aquatic populations or ecosystems. There is still further progress that can be made, including improving our appreciation of the implications of individual variation in movement patterns for management questions and further exploring movement patterns through the direct combination of acoustic telemetry with other complementary approaches.

The development and evolution of IMOS ATF and the national array over the past 10 years has been crucial to stimulating the widespread application of this technology in a coordinated fashion across estuarine and marine habitats, improving the outcomes from the substantial investments made by researchers in infrastructure and establishing new collaborations within the community. Broad-scale coordination of acoustic telemetry capability has not occurred to the same extent in fresh water in

Australia to date. However, with the burgeoning application of passive acoustic arrays across large river networks (e.g. the Murray–Darling Basin), there are many benefits to a more coordinated approach to array design and equipment or data sharing in the future. Indeed, the need for coordination of Australia's acoustic telemetry capability across the full range of aquatic habitats will likely continue as technology improves, and as novel challenges faced by natural resource managers necessitate improved knowledge of aquatic movement ecology to support informed and adaptive management.

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