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Abstract

Technologies for remotely observing animal movements have advanced rapidly in the past decade. In recent years, Australia has invested in an Integrated Marine Ocean Tracking (IMOS) system, a land ecosystem observatory (TERN), and an Australian Acoustic Observatory (A2O), but has not established movement tracking systems for individual terrestrial animals across land and along coastlines. Here, we make the case that the Motus Wildlife Tracking System, an open-source, rapidly expanding cooperative automated radio-tracking global network (Motus, https://motus.org) provides an unprecedented opportunity to build an affordable and proven infrastructure that will boost wildlife biology research and connect Australian researchers domestically and with international wildlife research. We briefly describe the system conceptually and technologically, then present the unique strengths of Motus, how Motus can complement and expand existing and emerging animal tracking systems, and how the Motus framework provides a much-needed central repository and impetus for archiving and sharing animal telemetry data. We propose ways to overcome the unique challenges posed by Australia's ecological attributes and the size of its scientific community. Open source, inherently cooperative and flexible, Motus provides a unique opportunity to leverage individual research effort into a larger collaborative achievement, thereby expanding the scale and scope of individual projects, while maximising the outcomes of scant research and conservation funding.

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A large-scale automated radio telemetry network for monitoring movements of terrestrial wildlife in Australia

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ABSTRACT

Technologies for remotely observing animal movements have advanced rapidly in the past decade. In recent years, Australia has invested in an Integrated Marine Ocean Tracking (IMOS) system, a land ecosystem observatory (TERN), and an Australian Acoustic Observatory (A2O), but has not established movement tracking systems for individual terrestrial animals across land and along coastlines. Here, we make the case that the Motus Wildlife Tracking System, an open-source, rapidly expanding cooperative automated radio-tracking global network (Motus, https://motus.org) provides an unprecedented opportunity to build an affordable and proven infrastructure that will boost wildlife biology research and connect Australian researchers domestically and with international wildlife research. We briefly describe the system conceptually and technologically, then present the unique strengths of Motus, how Motus can complement and expand existing and emerging animal tracking systems, and how the Motus framework provides a much-needed central repository and impetus for archiving and sharing animal telemetry data. We propose ways to overcome the unique challenges posed by Australia's ecological attributes and the size of its scientific community. Open source, inherently cooperative and flexible, Motus provides a unique opportunity to leverage individual research effort into a larger collaborative achievement, thereby expanding the scale and scope of individual projects, while maximising the outcomes of scant research and conservation funding.

Key words: automated telemetry; bat; insect; migration; Motus; movement ecology; telemetry; tracking technology; small animal; shorebird; songbird; water bird

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Introduction

Understanding animal movement is central to biodiversity conservation, wildlife management, and human and animal health (Kays *et al.* 2015, Fraser *et al.* 2018, Nimmo *et al.* 2018). Wildlife movements raise diverse challenges to which Australia responds by annually spending billions of dollars managing landscapes for connectivity and managing the spread of disease and invasive pests (Hurt *et al.* 2006, Haynes *et al.* 2009, Hansbro *et al.* 2010, Ree *et al.* 2011, Australian Government 2012a). Yet, for most land-dwelling species, we know little about which (e.g. age, sex), when, where and why individuals move, or about how small and large-scale movement patterns are changing in response to anthropogenic impacts, such as climate change, infrastructure development, and land use change. This is partly because Australia lacks a system that can track the movements of large numbers of individual animals across land and along coastlines in real-time at affordable cost. Without these data, the reliability and effectiveness of conservation and wildlife and disease management strategies and our ability to predict how our native wildlife communities will respond to rapid environmental change will be compromised.

There have been significant advances in technologies for quantifying animal movements in recent years (Cooke *et al.* 2004, Hussey *et al.* 2015, Kays *et al.* 2015). Capabilities of existing technologies have expanded and new developments are constantly in the pipeline. Among the methods used for tracking individual animals, radio telemetry is one of the oldest, yet despite this, digitization of transmitters and automation of receivers have breathed new life into the technology (Taylor *et al.* 2017). Geolocators are an archival light-logging technology that have revolutionized the study of the migration of small animals, particularly birds (McKinnon & Love 2018). By far the most prominent technological development is that of satellite-based systems, such as Global Positioning Systems (GPS), Argos, Iridium, and, most recently, the ICARUS initiative (reviewed by Wikelski *et al.* 2007). Satellite-based systems yield the promise of recording individual animal movements with unprecedented levels of spatial and temporal resolution in real-time with no other requirement than to catch an animal, attach a tag and switch on one's mobile phone (Wikelski *et al.* 2007, McKinnon & Love 2018). However, for all their strengths and future promise, all systems have limitations, including, but not limited to differences in cost, longevity and size of the animal-borne devices, and the spatiotemporal resolution and scale of the data collected. In our view, there is no Panacea/current system that suits all animal systems and all scientific questions. For this reason, the best outcomes will emerge by integrating available possibilities.

Here, we propose that an existing international coordinated automated radio telemetry array, the Motus Wildlife Tracking System (Motus, https://motus.org), provides an opportunity for Australia to invest in a national-scale terrestrial tracking infrastructure. The system is akin to Australia's Integrated Marine Observing System (IMOS, https://imos.org.au), capable of recording animal movements across land and coastlines at affordable cost. We briefly describe the primary features and capabilities of Motus, and address concerns surrounding the applicability of a large-scale automated radio telemetry network to the unique characteristics of Australia's wildlife and scientific communities. We consider that Motus in its current form already offers significant opportunities to study the movement ecology of our wildlife, but we argue that Australia should also see its national idiosyncrasies as a catalyst to contribute to developing this innovative technology.

Motus Wildlife Tracking System (Motus)

The concept

We summarise only the key features and capabilities of Motus. For a full overview of Motus compared to other available technologies for tracking animal movements, see the recent open access publication by Taylor *et al.* (2017) and Motus-related publications listed at https://motus.org.

Radiotracking of animals carrying VHF radio-transmitting tags has traditionally involved researchers on the ground or in aircraft using antennas and portable receivers to scour the landscape in search of signals. How many and how often animals are tracked is strictly limited by how many researchers can be deployed at any given time, the spatial extent of their coverage and the extent to which they can access the terrain. The concept of automating the collection of signal information from fixed receivers, that is, "automated radio telemetry", emerged in the early 1960s, facilitated by technological progress in electronics and computers (Cochran *et al.* 1965). There now exists several automated radio telemetry systems worldwide including Motus, Automated Radio Telemetry System, (ARTS) and the Biological AutomAted RAdiotelemetry System (BAARA) (Kays *et al.* 2011, Řeřucha *et al.* 2015).

What sets Motus aside from other automated radio telemetry systems is that it functions as an international network of collaborating researchers and organisations who manage independent arrays of receiving stations (Taylor *et al.* 2017). This cooperative approach provides significant advantages. First, tagged animals can be detected at multiple spatial scales, from local and regional, to global. Second, Motus benefits from pooled collective resources and knowledge of all researchers involved. The result is that all researchers' work is leveraged into a larger collaborative effort that expands the scale and scope while maximising scarce research and conservation funding.

The success of this open-source cooperative approach is evident from the rapid uptake the system has experienced globally. Instigated in 2012, the network now encompasses over 600 monitoring stations across 27 countries and six continents, including Australia (for an up-to-date map of stations, see https://motus.org/data/receiversMap). The network has supported more than 200 independent research projects, tagging over 16,000 individuals, spanning 180+ highly mobile species of bird, bat and flying insects. The system is currently being tested on large terrestrial mammals (see below) and its capabilities on small non-flying organisms (frogs, small lizards and mammals) remain to be examined (for an up-to-date list of projects and tracked species, see https://motus.org/explore-data/).

The collaborative approach is very powerful and mirrors those currently used in Australia in the marine context under the IMOS umbrella (Hussey *et al.* 2015, Brodie *et al.* 2018, Hoenner *et al.* 2018). IMOS animal tracking facility consists of nearly 1900 stations around Australia, monitoring 3777 tags fitted to 117 different marine species (Hoenner *et al.* 2018). As an illustration of the benefits of this collaborative approach, Bass and colleagues studied the movement of Port Jackson sharks (*Heterodontus portusjacksoni*) (Bass *et al.* 2017). They invested in a few receivers stationed in a specific breeding aggregation location in Jervis Bay, New South Wales (NSW), but the bay was already well equipped with receivers as part of an array maintained by the government department NSW Fisheries. Thus, Bass and colleagues could monitor breeding site fidelity and also track the sharks as they moved into and around the bay during the breeding season. In addition, there are a series of arrays along the east coast of Australia managed by several other research agencies, thus with no further investment they could also study large-scale migrations in their target species. They found that the sharks migrate to Tasmania and back each year. In addition, the collaborative dataset lends itself to ecosystem-wide analyses because multiple taxa are studied by multiple research groups simultaneously across various spatial scales (Brodie *et al.* 2018).

The technology

Motus employs Lotek Nanotags™ that emit a digital signal, the unique identity of which is encoded in the patterns of emitted pulses (Figure 1) (e.g. http://www.sirtrack.co.nz/index.php/avian/coded-vhf/all-attachments; http://www.lotek.com/vhf-radio-coded-transmitters.htm). Hence, unlike traditional 'beeper' VHF tags, each of which must transmit on one of a limited range of available frequencies, digital-encoding of tags means that the number of unique identities is essentially limitless, and thousands of tags can be deployed on the network at any given time (Figure 1). Tags range in mass from ~0.2 to 2.6 g, can last between 10 days and 3 years, and range in price from approximately AU$200-300 per unit depending on the size and the provider. There are multiple modes of attachment, including glue, sutures or harnesses (e.g. http://www.sirtrack.co.nz/index.php/avian/coded-vhf/all-attachments) (Figure 1).

Receiver stations comprise a power source, a receiver, and one or more antennas tuned to a specific frequency (currently 166.380 MHz in the Western Hemisphere; 150.100 MHz in Europe-Africa; 151.5 MHz in Australia). Currently, compatible receivers include Lotek SRX/DX series receivers (http://www.lotek.com/srx800.htm) or Sensorgnome receivers, a relatively low-cost receiver that can be built using open-source software and off-the-shelf hardware (www.sensorgnome.org). Receivers can 'listen' simultaneously to the signals of multiple close range omni and/or medium- to long-range directional Yagi antennas, which can be mounted on existing structures (e.g. buildings, lighthouses) or purpose-built structures such as antenna tripods (Figure 2). Receivers require a power source - either a direct connection to

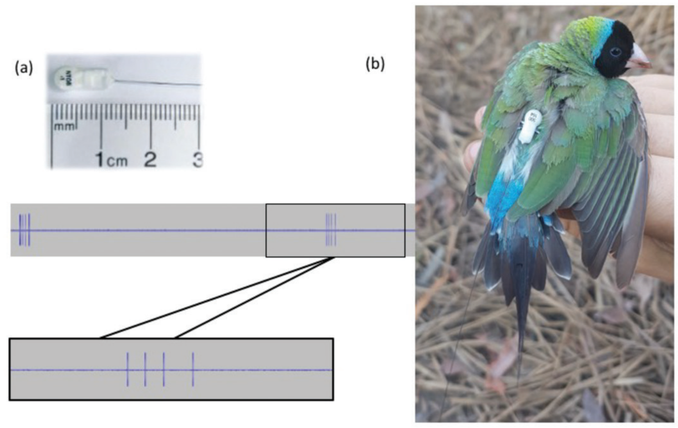

Figure 1: (a) Small, digitally encoded tag (above) and (below) its individually identifiable pulsatile signal structure. (b) A tagged Gouldian Finch

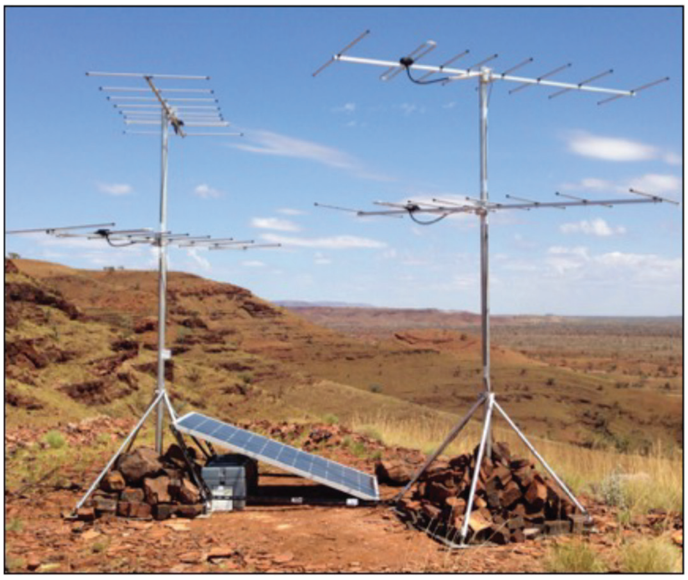

Figure 2: An example of an antenna configuration in Western Australia

the mains or solar-powered deep cycle batteries (Figure 2). Sensorgnome receivers allow for either a direct connection to the internet *via* Ethernet or a mobile phone network through which data can be transferred to the Motus database in real-time. Data from receivers not connected to the internet need to be downloaded manually. Simple instructions for building Sensorgnomes can be found at https://sensorgnome.org.

Where long-range directional antennas are deployed, tagged individuals are regularly detected simultaneously on Sensorgnome and Lotek receivers greater than 20 km apart (Mills *et al.* 2011) suggesting a *maximum* detection distance of 10-15 km. Long-distance detection is most likely when animals are in flight, well above the ground and in line of sight of the antenna. Many factors influence detection distance, including height and orientation of transmitting tags and receiving antennas and landscape features including topography, habitat and anthropogenic structures. Interference created by electromagnetic disturbances also reduces the effective detection distance, so stations are generally placed to minimize interference. The price of one receiving station including antennas and recievers varies significantly from between one and several thousand dollars, depending on design (e.g. mains powered versus solar-powered) and location (e.g. fixed to an existing structure versus stand-alone).

Using Motus requires adhering to the data flow designed and managed by the collective international consortium (Motus, https://motus.org, see Taylor *et al.* (2017) for more details). Motus is a program of Bird Studies Canada (BSC), Canada's leading science-based bird conservation and research organisation, in partnership with collaborating researchers from government, non-government, and academic organizations. Costs associated with data management, storage, and centralized processing are partially funded by a $1500 minimum annual deployment fee for the first 20 tags plus a one-off cost per tag of a few tens of Australian dollars for each additional tag collected by BSC. Prior to deployment, tags are registered with Motus which serves as a central repository of all tags on the global network and is hosted by BSC's National Data Centre. Users are required to include station, project and tag metadata, all of which are archived in the database and linked and managed through the Motus web platform. All tag detection data are linked to the master tag and station metadata to produce a complete database of unique detections from each station. Radio signals captured by the receivers are compared against the tag recordings submitted to Motus during tag registration. Minimal processing of raw detection data occurs prior to making data accessible to researchers. Once Motus has completed this initial processing, the principal investigator(s) of each project is provided access to a master project file which contains raw detection data including signal strength values, standard deviation in signal strength, and run length (number of continuous detections of a unique code by a receiver). In short, with this file, investigators can identify on which station and on which antenna within that station (if there are multiple antennas) their animals' tags were detected and when. By coupling this information with the open access station metadata (e.g. direction of the antenna, type of antenna (long-range versus omnidirectional)), the investigator can extract (see Figures 3-4 for examples): **1. Approximate positional information.** For example, the tag was detected means that animal was within the detection range of this antenna at this point in time, and closer if the signal strength is high versus further away if the signal strength is low (Figure 4). To assist in evalutating the effects of many confounding factors that influence the strength of the signal, tags can be ground-truthed during station installation. **2. Directional information.** For example, the signal strength might be strongest on an antenna pointing north-west meaning that the animal was located to the north-west of the station. If a tag was last detected on an antenna pointing south this means that the animal left the detection range of the antenna heading south at that detection time. **3. Activity and survival.** For example, the variance of the tag's signal strength across multiple successive detections on the same antenna can be low indicating that the animal is resting or dead, or it might be high indicating that the animal is active and perhaps foraging. 4. **High resolution temporal information.** Indeed, depending on the desired settings, a tag can be set to emit a pulse every 2-20 s.

Motus' strengths

Motus excels where small animals are studied and continuous detections with high temporal resolution are important (e.g. estimations of flight speed, fine-scale behaviour, timing of movements). Detections can be obtained 24/7 independent of time of day, weather conditions and/or human presence, generating more representative and less biased detections compared to traditional hand-held telemetry. Receiving stations can be arranged strategically to address project-specific questions. Stations can be placed at a stopover, roosting or breeding site and can gather information on activity (*via* fine-scale variation in signal strength), stopover duration, and arrival and departure timing. Other spatial arrangements include grids, small-world networks, and fence, circular and point-to-point arrays (Figure 5). Each of these can be deployed at a range of spatial scales (local to regional) and is ideally suited to asking different types of research questions (Taylor *et al.* 2017), many of which are particularly applicable within the Australian context. For example, small-world networks can be used to study species, such as nomadic waterbirds, which undertake mostly localised movements but also occasionally move long distances between locations (Hurt *et al*. 2006, Hansbro *et al.* 2010). Circular and grid arrays are well suited to measuring the timing and direction of movements from experimental release sites and can be used to gather settlement and survival data on wildlife reintroductions and translocations. Fence arrays are well suited to detecting when an animal passes by a specific landmark and can be used to study an advancing edge of a range expansion or invasion (Lermite 2018) (Figure 5). Fences can be placed perpendicular to roads or vegetation corridors depending on the type of pathway the animal is expected to use to measure usage. Receiving stations can also be relocated as research questions change.

The size of tags (~0.2-2.6 g) means that movement data can be collected on species and individuals (e.g. fledglings, juveniles) weighing as little as 7-10 g that cannot currently be tracked with other devices given the requirement for tags to weigh ideally less than 5% of the animal's body weight (Animal Research Review Panel 2015). For animals capable of housing tags on the 'heavier' end (1-2.6 g), long battery duration means that detections can occur over multiple years. Even when temporal resolution is minimized to maximise battery life, coded tags still emit a signal approximately every 20 s. Importantly, individuals need not be recaptured to access data, all of which is stored by the receiving stations, or streamed to Motus servers. The comparatively low cost of a tag and the automated detection of tags means that reasonable sample sizes examining the movement of different classes of individuals and inter-individual variation in movement patterns, and the use of experimental approaches become financially and logistically possible. Experimental designs, incorporating treatment and control groups that receive distinct manipulations, open new research avenues into investigating causality rather than merely describing patterns. Further, it also becomes possible to sample a much broader array of species, avoiding a polarization on large, flagship, and better-funded, but perhaps ecologically less-informative, species.

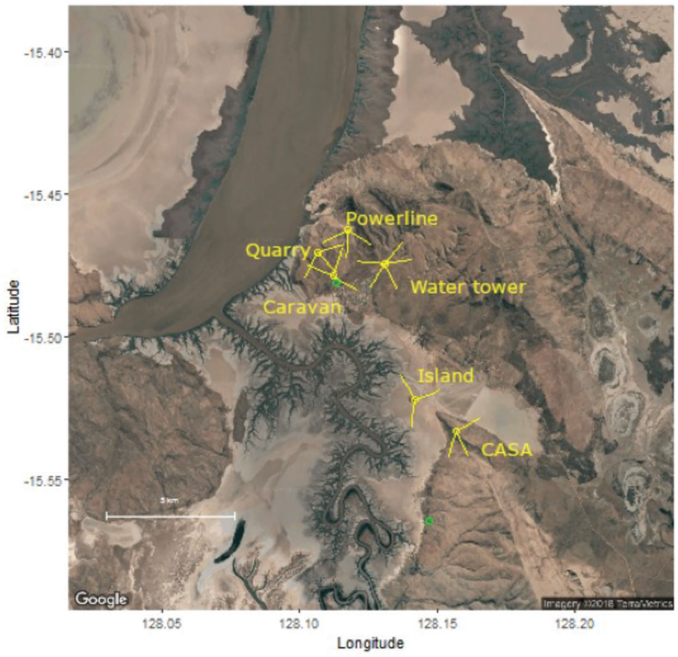

Figure 3: Location of receiving stations near the town of Wyndham in the East Kimberleys of Western Australia. Yellow lines show the bearing of 5-element directional Yagi antennas on each station. Note that the length of the line is not representative of antenna's detection range.

Motus studies can be used strategically to complement and expand other tracking technologies. For example, the migratory paths of a given species might be scoped using geolocators (GLS) to provide an initial idea of the general pathway a species covers during migration (McKinnon & Love 2018). Motus could then be employed to obtain more precise data on timing and location of migration, inter-individual variation in movement timing and strategies across years, and large, individually diverse sample sizes,

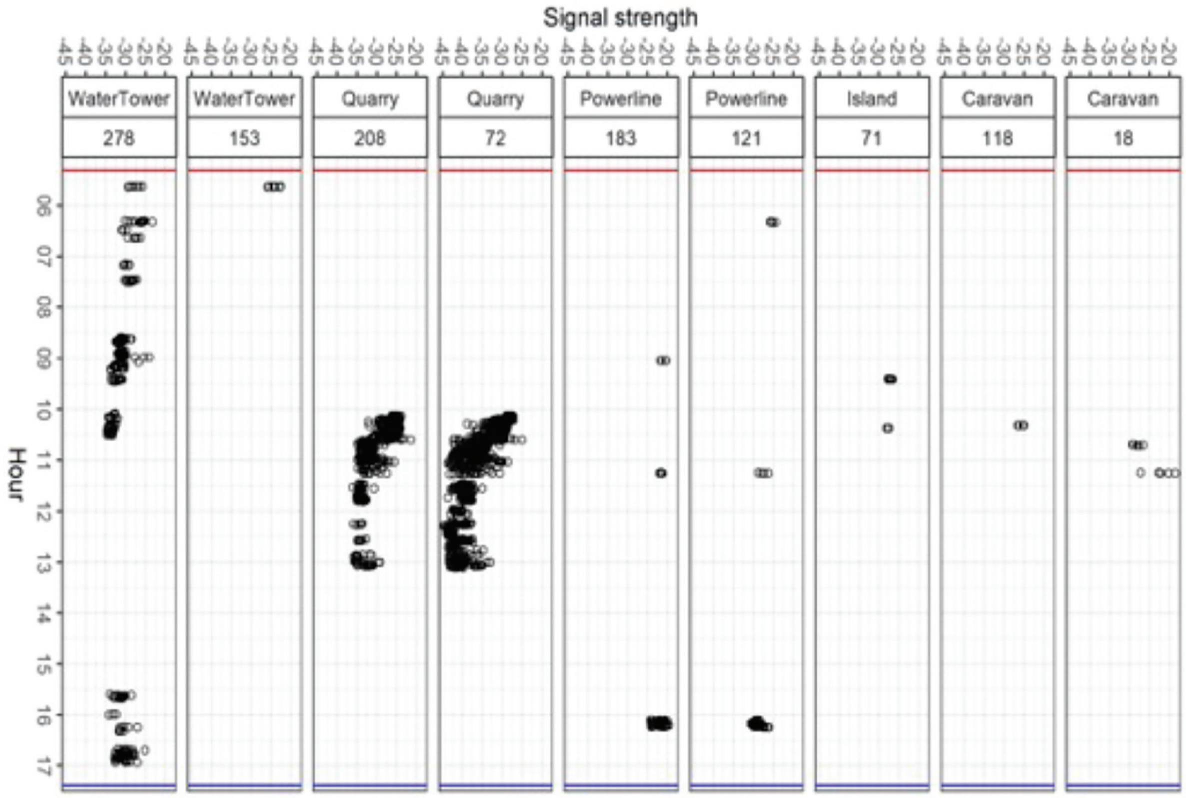

Figure 4: Example detections of a Gouldian Finch on 21 September 2018, captured with the station and antenna configuration shown in Figure 3. Each horizontal panel depicts the detections on a distinct antenna, the bearing or which is indicated in the panel label along side the station name (see Figure 3). Sunrise and sunset are shown by vertical red and blue lines, respectively. Tags were active from 5:00 – 17:00. In the morning, this tag was detected primarily by the Water Tower antenna with bearing 278 degrees, suggesting that the bird was east of the tower. A decline in signal strength on this antenna until approximately 10:30, and detection by the 72 and 208 bearing antennas on the Quarry station after 10:00 suggests the bird moved west from the Water Tower towards the Quarry station. A decline in signal strength at the Quarry antennas between 10:00-12:00 suggest the bird continued to move during this time. The large variability in signal strength around this decline is likely due to poorer signal detection (and lower signal strength) when the bird is on the ground foraging for seed, and higher signal detection (and higher signal strength) when the bird is actively moving. Few and simultaneous strong detections by the Powerline antenna oriented 183 and Caravan antenna oriented 18 degrees at approximately 11:15, suggest the bird was somewhere in between these three towers; triangulation of such simultaneous detections could be used to estimate a more precise position. Lower variability in signal strength between 11:30 and 12:30 suggests the bird was less active (possibly resting) during the heat of the day. Detections later in the afternoon (after 15:30) on the west-oriented Water Tower antenna (278) and south (183) and south-east (121) Powerline antennas suggest this individual moved back towards the Water Tower at the end of the day.

by strategically placing receiver stations in places identified by the GLS study. In addition to being used in strategic combinations with other tracking systems, the open source format and flexibility of Motus' digital system determines that it may in theory be tapped by any device that stores information digitally. Indeed, as the Sensorgnome receiver operates on open source software it could potentially be modified to communicate/receive data from any number of other tracking systems (e.g. satellite technology).

Finally, Motus by its very design creates a central repository of VHF telemetry data. This is because all detection data are stored by the Bird Studies Canada national data centre and Motus usage is predicated upon data sharing. Even though temporary embargoes can be placed on specific data sets by individual researchers, these are not encouraged (https://motus.org/policy/). Hence, Motus directly addresses the urgent need for greater sharing and re-using of animal tracking data (Campbell *et al.* 2015).

Is automated radio telemetry a viable long-term investment for Australia?

We envisage an Australian arm of the Motus network involving several 'small-world' grids, each one based in geographic regions with high research activity levels and/or research priorities (e.g. Eastern coastline, Western wetlands, North West). Together, these grids would capture tagged animals over multiple spatial scales (local, regional, national). Tagged animals that venture beyond our national boundaries would have the potential to be captured on the global Motus network (depending on how frequencies are allocated and sampled elsewhere, which might require the animal to be double tagged). In addition to the set, fixed (albeit movable) stations, 'mobile' stations could be available for users to borrow and deploy on a project-specific basis amongst (for greater spatial resolution) or between (for interconnectivity) existing grids. A land-based automated radio telemetry network in this form would provide the much-needed infrastructure to track individual animals across land, along coastlines, between the continent and offshore islands and in and out of the arid interior. It would constitute a matched terrestrial complement to IMOS, in which Australia invested over a decade ago, and is continuing to drive research and yield plethora information on our oceanic wildlife communities (Hoenner *et al*. 2018). We estimate that the cost of one such grid including 85 stations, 65 of which would be solar-powered and 50 of which would be stand-alone stations (i.e. not attached to existing structures) could be built for approximately $AU750,000.

That said, this form of Motus network could present some challenges. Here, we examine five potential challenges to a collaborative array in Australia and, in those cases where there is evidence that the challenges are real rather than imagined, we outline ongoing and planned developments that will alleviate those challenges. Our aim is to provide a realistic overview of the system's current and future potential in Australia, but also to highlight the part that Australia's researchers can and are playing towards the success of this remarkable global consortium.

1. Motus has only been used to track flying animals (birds, bats and insects), with a heavy focus on migratory birds. Australia's avian research community is far smaller than that in North America and Europe and a terrestrial network that can only track birds would represent an over-investment in comparison to the size of the research community.

Many of Australia's birds are nomadic and move in response to rainfall (Pedler *et al*. 2014, 2017, McEvoy *et al*. 2017). Thus, their movements do not follow highly predictable seasonal patterns and geographic pathways as in the Northern Hemisphere. As a result, it could be difficult to know where to set up receiving stations, and the expanse over which they should be deployed would seem excessive. We present four counter-arguments to these views.

First, while it is true that many Australian birds are nomadic, their movements are nevertheless not completely erratic. Indeed, 19 annual migration routes have been quantified for terrestrial birds moving within Australia and also over open water to international destinations (Griffioen & Clarke 2002), not to mention the 37 migratory shorebird species of the East Asian-Australasian Flyway that regularly occur in Australia. In addition, there are many well-known

Figure 5: An example of a receiver station configuration (fence) in North America. Each station is indicated as a yellow dot and the bearings of its antennas indicated with a yellow loop. Fences provide data on the time at which an animal passes by a given point and the direction in which it is heading. Grids provide within-grid local movement information. To create 'small world' grids, spatially separated grids can be interconnected by placing stations between them to obtain regional-level data on movements between grids.

breeding areas and many nomadic bird species appear there periodically (e.g. Macquarie Marshes, Gwydir Wetlands, Narran Lakes) (Bino *et al.* 2015, Pisanu *et al.* 2015). In other cases, there are well known areas where specific species have the potential to stopover and/or aggregate (to breed, to roost etc. (Hansbro *et al.* 2010)), for example, breeding areas of the Critically Endangered Regent Honeyeater (*Anthochaera Phrygia*, Roderick & Ingwersen 2014). The population of Regent Honeyeaters is being supplemented by releases of captive-bred birds. Monitoring of post-release survivorship and dispersion has been conducted using hand-held radio-tracking techniques, which have been done with enormous volunteer assistance and at significant economic cost. Capitalizing strategically on the synergies of Motus and other technologies to identify locations for potential Motus receiver deployment would provide a complementary approach to monitor known breeding areas, as well as identify potentially suitable breeding habitat on the basis of plant community composition and/or species presence/absence data from acoustic surveys, including Australia's recent continental acoustic observatory (A2O, https://acousticobservatory.org/) (Powys 2010, Roderick & Ingwersen 2014). Additionally, areas and travel routes of biological importance could be identified by tagging a few individual animals with satellite tags. Once these are known, some can be selected for receiving stations so that movements (and/or survival) can be monitored over multiple years in a cost-effective manner and with more individuals to understand how movement behaviour is learnt, what environmental cues trigger it, and the extent of inter-individual behavioural variation (Mitchell *et al.* 2015, Crysler *et al.* 2016). Viewed in this way, the Motus system is adaptable to a variety of critically important management needs.

Second, while at a national level, the research community working on migratory birds might be comparatively small relative to other parts of the world, Australia needs to consider its international commitments to conserving international flyways (Australian Government 2012b). Migratory shorebirds of the East Asian-Australasian Flyway are of high conservation concern in Australia owing to the steep and ongoing declines of many of these species since the 1970's (Clemens *et al.* 2016, Studds *et al.* 2017). Given that the broad-scale migration routes of shorebirds in this flyway are relatively well resolved and their habitat use is largely restricted to wetland and intertidal habitats, Motus is an ideal system for future research and monitoring of this group, as has been demonstrated in the Americas (e.g., Duijns *et al.* 2017; Munro 2017), and would greatly complement and value-add to existing and extensive monitoring, research, and conservation efforts by Australia's large community of wader study groups, volunteers, and researchers. Deployment of Motus stations at key migration, stopover, and non-breeding areas could provide insight into the migration phenology and survival of shorebirds in the flyway by allowing for large numbers of individuals of a variety of species to be tagged and their presence recorded at Motus checkpoints along Australia's coastlines, including remote and understudied areas in northern Australia and the Gulf of Carpentaria, and further north along the flyway. Building receiving stations along the flyway could also act to encourage neighbouring countries to join the international tracking effort and foster highly desirable international scientific collaboration in the Asia-Pacific region and grow the global impact of Australia's national research programs (Adams *et al.* 2016, Moores *et al.* 2016).

Third, Motus in Australia need not focus on birds. The system has proven its applicability to track bats, many of which are too small in Australia to use any other tagging technology. Given significant research, government and community interest in this diverse taxonomic group, quantifying the movement ecology of bats presents important opportunities beyond just birds (Law *et al.* 2011). Australia's smaller bats are mostly insectivores, while larger flying foxes feed on nectar, pollen, and fruit. Bats therefore have great functional importance in Australian ecosystems, but knowledge of the extent of their movements and potential for migration is limited, especially for smaller species (Eby 1991, Law & Lean 1999, Law *et al.* 2011, 2018, Roberts *et al.* 2012).

Already, Motus technology is being used in Western Australia to track movements of Ghost Bats (*Macroderma gigas*) and Pilbara Leaf-nosed Bats (*Rhinonicteris auranti*). Biologic Environmental Survey (https://www.biologicenv.com.au/) has deployed 77 active receivers in the Pilbara Region and bat tracking projects include linkages with major industries (e.g. BHP, Rio Tinto, Calidus Resources) and Perth Zoo. Findings are being used to improve decision making on how to minimise impact and also to better inform offset strategies.

Fourth, Motus's taxonomic specialization is much more a product of history than a consequence of any unsurmountable limitation of the technology. There is technically no reason why the Motus technology cannot be applied to ground- and tree-dwelling species although there may be some limitations regarding detection distances for these types of animals (Crewe *et al.* In press). In Western Australia, tests are underway by Biologic Environmental Survey to quantify the movements of Northern Quolls (*Dasyurus hallucatus*) and the first tags have been deployed and detected on receiver stations successfully. Ongoing technological developments of Motus will facilitate this extension. It is known that the range with which a station detects a tagged animal can vary significantly. For example, detection distances vary across habitats, but differential performances of this kind can be identified and accounted for. Due to the nature of VHF signals animals in flight are more readily detected and at greater ranges than animals on the ground, or under cover of vegetation, such as lizards and amphibians. Researchers are currently undertaking research to gain a better grasp of the environmental (e.g. vegetation) and technical (e.g. airborne vs terrestrial position) factors that influence signal detection (Crewe *et al*. In press), and how to incorporate variation in signal detection into data modelling.

In sum, in our experience many researchers are aware of the central importance of measuring movement, but technological and financial constraints have limited their ability to undertake such work. We predict that the advent of an innovative, affordable means of tracking large numbers of tagged animals will provide a catalyst to increase animal tracking studies in Australasia and boost movement ecology research on a broad range of taxonomic groups (Campbell *et al.* 2015). We also envisage that an Australian Motus telemetry network would be used by a far greater range of users than just academic researchers, including government (e.g. Commonwealth Scientific and Industrial Research Organisation (CSIRO); Department of Primary Industries (DPI), Road and Maritime Services (RMS)), and non-government wildlife research, protection, and rehabilitation agencies (WIRES, Science for Wildlife Limited), and industry (e.g. environmental agencies) users, as has been the case in North America and is beginning to be the case in Australia (e.g. Biologic Environmental Survey, https://www.biologicenv.com.au/).

2. Australia's climate and landscape can be extreme, posing unique challenges for the successful use of the technology to track wildlife in Australia.

Already, Motus technology is being used in Western Australia to track movements of the endangered Gouldian Finch in the East Kimberleys (HAC, TLC), and ghost bats in the Pilbara (TR). Because Australia's landscape is primarily uninhabitated and largely composed of rock and poor soils, the potential to attach receiving antennas to existing structures is limited, and anchoring stations to rock requires either labour-intensive drilling to secure the mast and guy wires to the ground, or use of rocks themselves as a counter-weight (Figure 2). Wildfires also burn frequently throughout Australia and pose a significant risk to infrastructure. To deal with this potential threat, receiver software can either be raised above ground, and/ or strategic late wet season burns around stations can limit the potential for more damaging and intense late dry season fires. The East Kimberleys regularly sees temperatures exceeding 40°C and is subject to frequent and extreme lightning storms during the wet season. Modifications to the typical sensorgnome receiver to deal with these challenges have included the use of lightning rods and grounding wire on towers, and surge protectors between the antenna and radio-receivers to protect the hardware and software of the sensorgnome. Radios are also attached to a metal plate with a heat sink, to dissipate heat and prevent temperature-related damage and malfunctioning of the sensorgnome. With these modifications, 6 receivers ran continuously despite extreme temperatures throughout September-November 2018 in the East Kimberleys. Data have been collected successfully, and are currently being analyzed to estimate how resource (water, seed) availability influences how Gouldian Finches interact with their environment, a key knowledge gap that will inform wildfire management decisions. Next year, the array will be expanded to capture the broader scale movements of this species, of which little is currently known.

3. The spatial resolution of Motus is comparatively low with respect to satellite-based systems, such as GPS.

While it is true that spatial resolution is comparatively low, Motus' proven history of success is evidence that imprecise position data are enough to address a rich diversity of questions. Nevertheless, positional estimates can be made when receivers or antennas are in proximity to one another (much like in manual telemetry) and station and antenna configurations that maximize the researchers' ability to make those estimates are continually being considered. Further development of state-space models will allow better representation of actual pathways that tagged individuals travel, with appropriate estimates of position error (Jonsen *et al.* 2005, Baldwin 2017). Given the heavy focus of Australian wildlife research on ground- and tree-dwelling animals such as koalas, kangaroos and introduced mammalian herbivores (e.g. deer, pigs, goats) and predators (foxes, cats), and key importance of monitoring zoonotic disease spread (Haynes *et al.* 2009, Vijaykrishna *et al.* 2013, Enchéry & Horvat 2017, Holz *et al*. 2018), Australia seems uniquely placed to drive the expansion of Motus into higher precision spatial estimates of land-bound animals, for example, with large-bodied ones that tend to roam in open habitats or high in tree tops. Detection parameters including station range and probability of detection within range could be estimated by double tagging land animals with GPS collars and coded tags. These data would allow one to infer how positional parameters from Motus compare with 'truth'. To date, such validation is most often undertaken within the context of specific projects. Motivations to capitalize on the advantages of the Motus technology might be high even when finances are available to use more expensive technologies. Indeed, it might be desirable to tag animals with VHF tags to avoid the need to recapture them, and potential health, ethical or public concerns involved in using large attachment devices (Hawkins 2004, Cid *et al*. 2013, Matthews *et al*. 2013).

4. Long-term maintenance of the network would be costly.

To date, rapid growth in the Motus system has occurred primarily from the ground up with organisations and researchers adding stations to the network through individual initiatives. This reduces the need for centralized maintenance costs since individual researchers have maintained their own stations. Nevertheless, all stations need some level of centralized oversight to ensure they remain in functioning order, and our experience to date is that these costs are important, and often overlooked. Costs per station vary significantly with the frequency and remoteness of visits required to download data and inspect the equipment. Solar-powered stations have higher maintenance costs than mains-powered ones, but even this varies greatly depending upon factors, such as weather exposure, equipment quality, and luck. Clearly, there would be costs to maintaining an Australian Motus network. We propose several approaches to ensuring centralized oversight and long-term maintenance over and above the responsibilities of individual researchers.

One possibility would be to charge a small one-off per tag levy, additional to that collected by Bird Studies Canada to support data management, that could be split between Australian cooperators proportional to the number of stations being maintained by the groups. We also envisage that commercial users could be charged a higher levy to account for the fact that industry earnings usually outweigh academic research earnings.

To ensure that the levy remains reasonable, however, there would be a need to lobby for government support and private sponsors. Potentially time-consuming, these activities would be nevertheless greatly facilitated by Bird Studies Canada's existing intensive online outreach activities (www.motus.org). The combination of technology and the immediate reward of observing the detailed movements of an animal, which can be made available online, constitutes an attractive option for sponsors. An Australian-based management team would benefit enormously from Motus' existing public platform. Motus' design is such that it can also respond flexibly to changing needs and resources. Stations with too high cost/low return ratios can be moved and/or removed, a management strategy that is commonly practiced within Motus, but also IMOS, to maximise returns (Rob Harcourt, pers. comm.).

Finally, two additional ongoing developments will help alleviate the concern of long-term maintenance costs. First, Motus is investigating systems for Sensorgnomes that will allow for remote monitoring and control of stations, with the ultimate aim of fully automating as many stations as possible (Taylor *et al.* 2017). Second, with some coordination and development, simple home-based receiver kits could be built and installed by citizen scientists (Taylor *et al.* 2017) vastly extending the range of the network. Mains-powered and installed on anthropogenic structures, such stations would have fewer maintenance costs and would contribute substantially to data collection. This initiative would provide expansion opportunities with little further increase in maintenance costs. Volunteers can also play an important role in the maintenance of stations and are already an invaluable component of the Motus apparatus in North America.

5. Motus might be outdated within the next 10 years given ongoing improvements, miniaturization of satellite-based systems and the advent of new technologies.

This concern can be alleviated by pointing to several features of the Motus system that make it relatively resilient to being superseded. From the beginning Motus has been designed to be agnostic to tag and receiver types. It is intended as a fully open source platform for research with radio telemetry. Specifically, the open source format and flexibility of the digital system means that Motus can be used in synergy with other systems, protecting its utility in the long-term. As the Sensorgnome receiver operates on open source software it can thus, in theory, be programmed to communicate/receive data from any number of other tracking systems. For example, there is at present a new initiative to integrate the data flow from Cellular Tracking Technolgies (CTT; www.celltracktech.com) 'LifeTags', a global, solar-powered tag on a frequency of 434 MHz. In a further example, it is also possible that Motus receivers could be paired with other types of receivers (e.g. Icarus base stations) to help facilitate the flow of data and the maintenance of on-the-ground infrastructure. We see future developments of the system arising from multi-institutional collaborations; implementing these in an open and collaborative framework will be our next challenge. Other tags and receiver types will be developed in the future, and our aim is to provide the global infrastructure to ensure that these initiatives can act synergistically rather than in competition.

Finally, we also argue that being superseded is a challenge that faces all fields of scientific study with rapidly developing technologies (e.g. genomics). Yet, holding off investment until the ultimate technological advance has become available is hardly wise. While we eagerly await the technological revolution whereby thousands of tags, including ones that can be attached to very small animals, can be deployed at affordable cost and transmitting to our mobile phones in real-time, we suggest that the task of quantifying the movements of our native and introduced terrestrial fauna and how these are changing in response to human-induced rapid environmental change is too urgent to be put on hold.

Conclusions

Australia has an urgent need for an affordable system to boost movement ecology research on native and introduced terrestrial animals. Such data are imperative to support and guide landscape and wildlife management and conservation now and into the future. Australia could also benefit from a system by which animal movement data can be shared at a global scale (but see ZoaTrack for an Australian-based initiative, https://zoatrack.org/). We make the case that the Motus Wildlife Tracking System, a globally-focused, rapidly expanding cooperative automated radio-tracking technology (https://motus.org) provides an unprecedented opportunity for Australia to invest in wildlife biology and to connect Australian-based research to a global network. An Australian-based Motus network of ground receiving stations will provide the infrastructure to track individual animals across land, along coastlines, between the continent and offshore islands, and within, and in and out of, the arid interior. The network will also provide a central repository for telemetry data and impetus for data sharing. Open source and inherently flexible, Motus complements and expands existing and emerging animal tracking systems. Current work is showing that Motus is well-suited to Australia's wildlife and Australia's research community. While the research community is small, it is well equipped and motivated to embrace and expand movement ecological research and partake in Motus developments, an affordable and proven technological opportunity.

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References

Adams, V.M., Spindler, R.E., and Kingsford, R.T. 2016. Thinking globally, acting locally - Conservation lessons from Oceania. *Pacific Conservation Biology* **22**: 85–89. doi:10.1071/PCv22n2_ED.

Animal Research Review Panel. 2015. Radio tracking in wildlife research. Available from https://www.animalethics.org.au/policies-and-guidelines/wildlife-research/radio-tracking.

Australian Government. 2012a. National wildlife corridors plan: a framework for landscape-scale conservation. Department of Sustainability, Environment, Water, Population and Communities. Available from https://trove.nla.gov.au/work/175714575?selectedversion=NBD50419849.

Australian Government. 2012b. Australia's obligations under the Ramsar convention: legislative support for wetlands - Fact sheet. Department of Sustainability, Environment, Water, Population and Communities. Available from http://www.environment.gov.au/water/wetlands/publications/australias-obligations-under-ramsar-convention-legislative-support-wetlands-fact-sheet.

Baldwin, J. 2017. Modelling Bird Migration with Motus Data and Bayesian State-Space Models. Masters Theses. 565. University of Massachusetts Amherst.

Bass, N.C., Mourier, J., Knott, N.A., Day, J., Guttridge, T., and Brown, C. 2017. Long-term migration patterns and bisexual philopatry in a benthic shark species. *Marine and Freshwater Research* **68**: 1414–1421. doi:10.1071/MF16122.

Bino, G., Sisson, S.A., Kingsford, R.T., Thomas, R.F., and Bowen, S. 2015. Developing state and transition models of floodplain vegetation dynamics as a tool for conservation decision-making: A case study of the Macquarie Marshes Ramsar wetland. *Journal of Applied Ecology* **52**: 654–664. doi:10.1111/1365-2664.12410.

Brodie, S., Lédée, E.J.I., Heupel, M.R., Babcock, R.C., Campbell, H.A., Gledhill, D.C., Hoenner, X., Huveneers, C., Jaine, F.R.A., Simpfendorfer, C.A., Taylor, M.D., Udyawer, V., and Harcourt, R.G. 2018. Continental-scale animal tracking reveals functional movement classes across marine taxa. *Scientific Reports* **8**: 3717. doi:10.1038/s41598-018-21988-5.

Campbell, H.A., Beyer, H.L., Dennis, T.E., Dwyer, R.G., Forester, J.D., Fukuda, Y., Lynch, C., Hindell, M.A., Menke, N., Morales, J.M., Richardson, C., Rodgers, E., Taylor, G., Watts, M.E., and Westcott, D.A. 2015. Finding our way: On the sharing and reuse of animal telemetry data in Australasia. *Science of the Total Environment* **534**: 79–84. doi:10.1016/j.scitotenv.2015.01.089.

Cid, B., Costa, R. de C. da, Balthazar, D. de A., Augusto, A.M., Pires, A.S., and Fernandez, F.A.S. 2013. Preventing injuries caused by radiotelemetry collars in reintroduced red-rumped agoutis, *Dasyprocta leporina* (Rodentia: Dasyproctidae), in Atlantic Forest, southeastern Brazil. *Zoologia* **30**: 115–118. doi:10.1590/S1984-46702013000100015.

Clemens, R.S., Rogers, D.I., Hansen, B.D., Gosbell, K., Minton, C.D.T., Straw, P., Bamford, M., Woehler, E.J., Milton, D.A., Weston, M.A., Venables, B., Weller, D., Hassell, C., Rutherford, B., Onton, K., Herrod, A., Studds, C.E., Choi, C.Y., Dhanjal-Adams, K.L., Murray, N.J., Skilleter, G.A., and Fuller, R.A. 2016. Continental-scale decreases in shorebird populations in Australia. *Emu* **116**: 119–135. doi:10.1071/MU15056.

Cochran, W.W., Warner, D.W., Tester, J.R., and Kuechle, V.B. 1965. Automatic Radio-Tracking System for Monitoring Animal Movements. *BioScience* **15**: 98–100. Available from http://dx.doi.org/10.2307/1293346.

Cooke, S.J., Hinch, S.G., Wikelski, M., Andrews, R.D., Kuchel, L.J., Wolcott, T.G., and Butler, P.J. 2004. Biotelemetry: a mechanistic approach to ecology. *Trends in Ecology & Evolution* **19**: 334–43. doi:10.1016/j.tree.2004.04.003.

Crewe, T.L., Deakin, J., Beauchamp, A., and Morbey, Y. (In press). Detection range of songbirds using a stopover site by automated radio-telemetry. *Journal of Field Ornithology*. doi:10.111/jofo.12291.

Crysler, Z.J., Ronconi, R.A., Taylor, P. 2016. Differential fall migratory routes of adult and juvenile Ipswich Sparrows (*Passerculus sandwichensis princeps*). *Movement Ecology* **4**: 3. doi:10.1186/s40462-016-0067-8.

Duijns, S., Niles, L.J., Dey, A., Aubry, Y., Friis, C., Koch, S., Anderson, A.M., and Smith, P.A. 2017. Body condition explains migratory performance of a long-distance migrant. *Proceedings of the Royal Society B* **284:** 20171374. doi:10.1098/rspb.2017.1374.

Eby, P. 1991. Seasonal movements of grey-headed flying-foxes, *Pteropus poliocephalus* (Chiroptera : Pteropodidae), from two maternity camps in northern New South Wales. *Wildlife Research* **18**: 547–559. Available from https://doi.org/10.1071/WR9910547.

Enchéry, F., and Horvat, B. 2017. Understanding the interaction between henipaviruses and their natural host, fruit bats: Paving the way toward control of highly lethal infection in humans. *International Reviews of Immunology* **36**: 108–121. doi:10.1080/08830185.2016.1255883.

Fraser, K.C., Davies, K.T.A., Davy, C.M., Ford, A.T., Flockhart, D.T.T., and Martins, E.G. 2018. Tracking the Conservation Promise of Movement Ecology. *Frontiers in Ecology and Evolution* **6:** 150 Available from https://www.frontiersin.org/article/10.3389/fevo.2018.00150.

Griffioen, P., and Clarke, M. 2002. Large-scale bird-movement patterns evident in eastern Australian atlas data. *Emu* **102**: 99–125.

Hansbro, P.M., Warner, S., Tracey, J.P., Arzey, K.E., Selleck, P., O'Riley, K., Beckett, E.L., Bunn, C., Kirkland, P.D., Vijaykrishna, D., Olsen, B., and Hurt, A.C. 2010. Surveillance and analysis of avian influenza viruses, Australia. *Emerging Infectious Diseases* **16**: 1896–1904. doi:10.3201/eid1612.100776.

Hawkins, P. 2004. Bio-logging and animal welfare: practical refinements. *Memoirs of National Institute of Polar Research* **58**: 58–68.

Haynes, L., Arzey, E., Bell, C., Buchanan, N., Burgess, G., Cronan, V., Dickason, C., Field, H., Gibbs, S., Hansbro, P.M., Hollingsworth, T., Hurt, A.C., Kirkland, P., McCracken, H., O'Connor, J., Tracey, J., Wallner, J., Warner, S., Woods, R., and Bunn, C. 2009. Australian surveillance for avian influenza viruses in wild birds between July 2005 and June 2007. *Australian Veterinary Journal* **87**: 266–272. doi:10.1111/j.1751-0813.2009.00446.x.

Hoenner, X., Huveneers, C., Steckenreuter, A., Simpfendorfer, C., Tattersall, K., Jaine, F., Atkins, N., Babcock, R., Brodie, S., Burgess, J., Campbell, H., Heupel, M., Pasquer, B., Proctor, R., Taylor, M.D., Udyawer, V., and Harco, R. 2018. Data Descriptor: Australia's continental-scale acoustic tracking database and its automated quality control process. *Scientific Data* **5**: 180206. doi:10.1038/sdata.2017.206.

Holz, P.H., Lumsden, L.F., Druce, J., Legione, A.R., Vaz, P., Devlin, J.M., and Hufschmid, J. 2018. Virus survey in populations of two subspecies of bent-winged bats (*Miniopterus orianae bassanii* and *oceanensis*) in south-eastern Australia reveals a high prevalence of diverse herpesviruses. *PLoS ONE* **13(5)**: e0197625. doi:10.1371/journal.pone.0197625.

Hurt, A.C., Hansbro, P.M., Selleck, P., Olsen, B., Minton, C., Hampson, A.W., and Barr, I.G. 2006. Isolation of avian influenza viruses from two different transhemispheric migratory shorebird species in Australia. *Archives of Virology* **151**: 2301–2309. doi:10.1007/s00705-006-0784-1.

Hussey, N.E., Kessel, S.T., Aarestrup, K., Cooke, S.J., Cowley, P.D., Fisk, A.T., Harcourt, R.G., Holland, K.N., Iverson, S.J., Kocik, J.F., Mills Flemming, J.E., and Whoriskey, F.G. 2015. Aquatic animal telemetry: A panoramic window into the underwater world. *Science* **348**: 1255642. doi:10.1126/science.1255642.

Jonsen, I.D., Flemming, J.M., and Myers, R.A. 2005. Robust state-space modeling of animal movement data. *Ecology* **86**: 2874–2880. doi:10.1890/04-1852.

Kays, R., Crofoot, M.C., Jetz, W., and Wikelski, M. 2015. Terrestrial animal tracking as an eye on life and planet. *Science* **348**: aaa2478. doi:10.1126/science.aaa2478.

Kays, R., Tilak, S., Crofoot, M., Fountain, T., Obando, D., Ortega, A., Kuemmeth, F., Mandel, J., Swenson, G., Lambert, T., Hirsch, B., and Wikelski, M. 2011. Tracking animal location and activity with an automated radio telemetry system in a tropical rainforest. *The Computer Journal* **54**: 1931–1948. doi:10.1093/comjnl/bxr072.

Law, B., Doty, A., Chidel, M., and Brassil, T. 2018. Bat activity before and after a severe wildfire in Pilliga forests: Resilience influenced by fire extent and landscape mobility? *Austral Ecology* **43**: 706–718. doi:10.1111/aec.12617.

Law, B., Eby, P., Lunney, D., and Lumsden, L. 2011. The Biology and Conservation of Australasian Bats. *Edited By* B. Law, P. Eby, D. Lunney, and L. Lumsden. Royal Zoological Society of New South Wales. doi:10.7882/9780980327243.

Law, B., and Lean, M. 1999. Common blossom bats (*Syconycteris australis*) as pollinators in fragmented Australian tropical rainforest. *Biological Conservation* **91**: 201–212.

Lermite, F. 2018. Biological, behavioural and life history traits associated with range expansion of common mynas (*Acridotheres tristis*) in Australia. PhD thesis. University of Newcastle, Australia.

Matthews, A., Ruykys, L., Ellis, B., FitzGibbon, S., Lunney, D., Crowther, M.S., Glen, A.S., Purcell, B., Moseby, K., Stott, J., Fletcher, D., Wimpenny, C., Allen, B.L., Van Bommel, L., Roberts, M., Davies, N., Green, K., Newsome, T., Ballard, G., Fleming, P., Dickman, C.R., Eberhart, A., Troy, S., McMahon, C., and Wiggins, N. 2013. The success of GPS collar deployments on mammals in Australia. *Australian Mammalogy* **35**: 65–83. doi:10.1071/AM12021

McEvoy, J., Ribot, R., Wingfield, J., and Bennett, A. 2017. Heavy rainfall triggers increased nocturnal flight in desert populations of the Pacific black duck (*Anas superciliosa*). *Scientific Reports* **7**: 17557. doi:10.1038/s41598-017-17859-0.

McKinnon, E.A., and Love, O.P. 2018. Ten years tracking the migrations of small landbirds: Lessons learned in the golden age of bio-logging. *The Auk* **135**: 834–856. doi:10.1642/AUK-17-202.1.

Mills, A.M., Thurber, B.G., Mackenzie, S.A., and Taylor, P. 2011. Passerines use nocturnal flights for landscape-scale movements during migration stopover. The *Condor* **113**: 597–607. doi:10.1525/cond.2011.100186.

Mitchell, G.W., Woodworth, B.K., Taylor, P., and Norris, D.R. 2015. Automated telemetry reveals age specific differences in flight duration and speed are driven by wind conditions in a migratory songbird. *Movement ecology* **3**: 19. doi:10.1186/s40462-015-0046-5.

Moores, N., Rogers, D.I., Rogers, K., and Hansbro, P.M. 2016. Reclamation of tidal flats and shorebird declines in Saemangeum and elsewhere in the Republic of Korea. *Emu* **116**: 136–146. doi:10.1071/MU16006.

Munro, M. 2017. What's killing the world's shorebirds? *Nature* **541**: 16–20. doi:10.1038/541016a.

Nimmo, D.G., Avitabile, S., Banks, S.C., Bliege Bird, R., Callister, K., Clarke, M.F., Dickman, C.R., Doherty, T.S., Driscoll, D.A., Greenville, A.C., Haslem, A., Kelly, L.T., Kenny, S.A., Lahoz-Monfort, J.J., Lee, C., Leonard, S., Moore, H., Newsome, T.M., Parr, C.L., Ritchie, E.G., Schneider, K., Turner, J.M., Watson, S., Westbrooke, M., Wouters, M., White, M., and Bennett, A.F. 2018. Animal movements in fire-prone landscapes. *Biological Reviews:* **94:** 981-998. doi:10.1111/brv.12486.

Pedler, R., Ribot, R., and Bennett, A. 2014. Extreme nomadism in desert waterbirds: Flights of the banded stilt. *Biology Letters* **10**: 20140547. doi:10.1098/rsbl.2014.0547.

Pedler, R., Ribot, R., and Bennett, A. 2017. Long-distance flights and high-risk breeding by nomadic waterbirds on desert salt lakes. *Conservation Biology* **32**: 216–228. doi:10.1111/cobi.13007.

Pisanu, P., Kingsford, R.T., Wilson, B., and Bonifacio, R. 2015. Status of connected wetlands of the Lake Eyre Basin, Australia. *Austral Ecology* **40**: 460–471. doi:10.1111/aec.12203.

Powys, V. 2010. Regent honeyeaters - Mapping their movements through song. *Corella* **34**: 92–102.

Ree, R. Van Der, Jaeger, J.A.G., Grift, E.A. Van Der, and Clevenger, A.P. 2011. Effects of roads and traffic on wildlife populations and landscape function: road ecology is moving toward larger scales. *Ecology and Society* **16**: 48. doi:10.5751/ES-03982-160148.

Rerucha, S., Bartonicka, T., Jedlička, P., Čížek, M., Hlouša, O., Lučan, R., and Horacek, I. 2015. The BAARA (Biological AutomAted RAdiotracking) System: A new approach in ecological field studies. *PloS ONE* **10(2):** e0116785. doi:10.1371/journal.pone.0116785.

Roberts, B.J., Catterall, C.P., Eby, P., and Kanowski, J. 2012. Long-distance and frequent movements of the flying-fox *Pteropus poliocephalus*: Implications for management. PLoS One, **7(8)**: e42532. doi:10.1371/journal.pone.0042532.

Roderick, M., and Ingwersen, D.A. 2014. Swift Parrots and Regent Honeyeaters in the Lake Macquarie City Council area New South Wales: an assessment of status, identification, of high priority habitats and recommendations for conservation. Report for Lake Macquarie Council.

Studds, C.E., Kendall, B.E., Murray, N.J., Wilson, H.B., Rogers, D.I., Clemens, R.S., Gosbell, K., Hassell, C.J., Jessop, R., Melville, D.S., Milton, D.A., Minton, C.D.T., Possingham, H.P., Riegen, A.C., Straw, P., Woehler, E.J., and Fuller, R.A. 2017. Rapid population decline in migratory shorebirds relying on Yellow Sea tidal mudflats as stopover sites. *Nature Communications* **8:** 14895. doi:10.1038/ncomms14895.

Taylor, P., Crewe, T.L., Mackenzie, S.A., Lepage, D., Aubry, Y., Crysler, Z., Finney, G., Francis, C.M., Guglielmo, C.G., Hamilton, D.J., Holberton, R.L., Loring, P.H., Mitchell, G.W., Norris, D.R., Paquet, J., Ronconi, R.A., Smetzer, J.R., Smith, P.A., Welch, L.J., and Woodworth, B.K. 2017. The Motus wildlife tracking system: A collaborative research network to enhance the understanding of wildlife movement. *Avian Conservation and Ecology* **12**: 8. doi:10.5751/ACE-00953-120108.

Vijaykrishna, D., Deng, Y.-M., Su, Y., Fourment, M., Lannello, P., Arzey, G., Hansbro, P., Arzey, E., Kirkland, P., Warner, S., O'Riley, K., Barr, I., Smith, G., and Hurt, A. 2013. The recent establishment of North American h10 lineage influenza viruses in Australian wild waterfowl and the evolution of Australian avian influenza viruses. *Journal of Virology* **87**: 10182–10189. doi:10.1128/JVI.03437-12.

Wikelski, M., Kays, R.W., Kasdin, N.J., Thorup, K., Smith, J.A., and Swenson, G.W. 2007. Going wild: what a global small-animal tracking system could do for experimental biologists. *Journal of Experimental Biology* **210**: 181–186. doi:10.1242/jeb.02629.